Doppler Acoustic Radar Observations Of Wind in the Ellerslie Region Of Alberta

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DOPPLER ACOUSTIC RADAR OBSERVATIONS OF WIND IN THE ELLERSLIE REGION OF ALBERTA

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DOPPLER ACOUSTIC RADAR OBSERVATIONS OF WIND IN THE ELLERSLIE REGION OF ALBERTA

by

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for

RESEARCH MANAGEMENT DIVISION
Alberta Environment

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ABSTRACT

Horizontal and vertical wind speeds, wind direction, and turbulence in the lower 500 m of the atmosphere are observed continuously by Doppler acoustic radar at Alberta Environment's air pollution meteorology station, located in a rural agricultural area 5 km west of Ellerslie, Alberta. Data observed between 1982 September 01 and 1983 August 31 have been summarized and evaluated as functions of time, height, and stability.

Radar reporting efficiency was greatest for lower levels and in unstable atmospheres. Only about 40 percent of all observed profiles reached 500 m. Quality control procedures were initiated because of discrepancies between lower level radar data and winds at the 10- and 20-m levels collected from the on-site meteorological tower. Reported radar winds at 50 and 100 m were found to be unreliable. These data were excluded from subsequent analyses.

Winds were predominantly southeasterly at 20 m and northwesterly at 500 m. Veering with height occurred about 70 percent of the time, with median directional changes between levels agreeing with values reported in the literature.

Horizontal wind speeds increased with height about 70 percent of the time. Behaviours were satisfactorily explained with the well known log and power law relations. Values for the roughness length and power law exponent for neutral atmospheres, as derived from a combination of meteorological tower and Doppler wind information extending from 10 to 500 m, were much smaller than comparable values obtained only from the Doppler wind data collected at or above 150 m. Roughness lengths calculated with the log law were not constant as required by theory, but ranged over three orders of magnitude. Their median value and standard deviation as obtained from a combination of meteorological tower and Doppler wind data were 0.33 and 3.0 m, respectively.

Frictional velocities calculated from the log law had a median of 0.35 mS^{-1} with a standard deviation of 0.3 ms^{-1}, while friction velocities calculated from longitudinal turbulence had a median of 0.45 ms^{-1} with a standard deviation of 1.3 ms^{-1}. Because

of the large difference in standard deviations, it was concluded that friction velocities determined by the two methods are not equivalent.

Turbulence levels depended only slightly on wind direction, with higher turbulence associated with northwesterly winds. Horizontal turbulence tended to increase with height for all atmospheric stabilities and to be greater with higher wind speeds. Vertical turbulence tended to decrease with height and be independent of wind speed. Longitudinal and lateral components of turbulence were nearly equal. Ratios of vertical to horizontal turbulence were near unity at about 100 m but decreased to about 0.2 at 500 m.

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1. INTRODUCTION

Alberta Environment maintains a meteorological station about 5 km west of Ellerslie, Alberta. The station is located in an agricultural area characterized by relatively flat terrain, cultivated fields, and stands of trees.

Measurements of wind are made at the site using a Doppler acoustic radar manufactured by Xontech. Discussions of the principles of radar operation may be found in the general literature (e.g. Balser et al. 1976).

Doppler wind speeds and directions are accurate to within 0.1 ms^{-1} and one degree, respectively. Time and space averaged data are available hourly at ten elevations ranging from 50 to 500 m for horizontal and vertical wind speeds, wind direction, and standard deviations of these parameters. All hourly standard deviations are calculated automatically from measurements of two-minute means and standard deviations. Tables of information printed by the Doppler instrument were keypunched by double entry, checked for accuracy, and subsequently transferred to a nine track tape. An instrumented tower is used to collect wind information near the ground (10 and 20 m) to supplement data derived from the Doppler radar.

The Doppler acoustic radar computes the speed of the mean vector wind. Wind speeds have classically been assessed through the use of cup anemometers which measure the mean speed of the horizontal component of the wind. These two quantities will differ if the fluctuations in wind direction are not negligibly small. Setting the x axis along the mean wind vector, U, and denoting the instanteous horizontal wind speed as V_h, the two are related by the expression:

$$U = V_h \cos \theta \qquad (1)$$

where θ is the deviation of the instantaneous azimuth angle from that of the mean wind vector. Bernstein (1967) has shown that the mean values, $\bar{U}$ and $\bar{V}$, are approximately related:

$$\bar{U} \simeq \bar{V}_h \exp\left(-\tfrac{1}{2}\sigma_\theta^2\right) \qquad (2)$$

where σ_θ (radians) is the standard deviation of the azimuth angle over the averaging period. According to equation (2), $\bar{U}$ will be about 98, 94 and 87 percent of the $\bar{V}_h$ values when σ_θ equals 10, 20 and 30 degrees, respectively. Because typical values for σ_θ under stable, neutral and unstable atmospheric conditions are about 5, 10 and 20 degrees respectively (Gifford 1968), values of $\bar{U}$ and $\bar{V}_h$ should usually be similar.

Behaviour patterns of wind velocity and turbulence have been extensively studied and reported in the literature. A review of the large body of available information would constitute a major task beyond the scope of the present study. Fortunately Hanna et al. (1982) recently finished such an undertaking. They have recommended what they consider the best current formulas for assessing atmospheric phenomena. Their findings have been relied upon in this initial review of Doppler radar data collected at Ellerslie. Most of the studies reviewed by Hanna et al. are based on data collected within the first 50 m or so of the atmosphere. Information from the Ellerslie acoustic radar will provide some of the first detailed knowledge at heights beyond 150 m.

This report presents results of data analyses from the first year of Doppler acoustic radar operation (1982 September 1 to 1983 August 31). A quality control was first instituted to ensure that radar information was reliable. This was necessitated by discrepancies between data collected by radar and those collected by the conventional tower mounted instruments. There was particular concern about data collected during a two-month period (December 1982 to January 1983) when there were problems with the electrical circuitry. A detailed analysis was performed with data deemed acceptable to determine variations in observed parameters at each level, and to ascertain the manner in which these parameters changed with height.

While the emphasis in this report is on atmospheric behaviour, it is ultimately the implication to plume behaviour which is of most practical interest. For this reason, consequences of the more important characteristics of upper air turbulence demonstrated in this study are briefly discussed.

2. THEORY

Wind behaviour at Ellerslie might reasonably be expected to approximate that of air flowing over flat terrain. There exists a very large body of theory relating to this phenomenon. Such theory usually views the atmosphere as being divided into two layers: the surface stress layer and the spiral layer. In the surface stress layer, influences of frictional forces on air motions are more important than those of forces attributable to the horizontal pressure gradient or to the rotation of the earth (Coriolis force). Within the spiral layer all three forces are of about equal magnitude. There is some debate about the relative thickness of the two atmospheric layers. It appears, however, that the surface stress layer extends to about 50 m while the spiral layer extends from this level upwards beyond 500 m (Hanna et al. 1982). Thus most of the Doppler radar information will be relevant only to spiral layer behaviour.

2.1 SURFACE STRESS LAYER

Within the surface stress layer, the wind direction and turbulence are assumed to be constant with height. Wind speeds, however, are usually found to increase with elevation above the ground.

2.1.1 Vertical Variation in Wind Speeds

Within the surface layer, the vertical gradient of the horizontal wind speed is often assumed to vary inversely with height. Thus,

$$\frac{d\bar{U}}{dZ} = \frac{C}{Z} \qquad (3)$$

where:

$\bar{U}$ = mean wind speed

Z = height above the earth's surface

The proportionality coefficient, C, has the dimensions of wind speed. It is denoted as $U_{\star}\Phi k^{-1}$ where $U_{\star}$ is called the friction velocity and k is the von Karman constant (usually assumed to have a value of 0.4). The additional parameter, Φ, called the diabatic influence function, is a multiplication factor which is found to vary with stability and height. Equation (3) may now be rewritten as:

$$\frac{d\bar{U}}{dZ} = \frac{U_{\star}\,\Phi}{kZ} \tag{4}$$

Friction velocities will generally be a function of ground roughness, turbulence levels, vertical heat fluxes, horizontal pressure gradients and mixing depths. Data presented by Gifford (1968) suggest that a typical value of $U_{\star}$ for Ellerslie (which is surrounded by grassy fields) under neutral conditions should be about 0.5 m s^{-1}. It is more difficult to estimate $U_{\star}$ for unstable and stable atmospheric conditions because of complications arising from heat flux. It has been postulated that $U_{\star}$ should always be closely associated with the level of mechanical turbulence. The following approximations should provide reasonable values for $U_{\star}$ (Binkowski 1979):

$$U_{\star} = \frac{\sigma_U}{2.1} \quad \text{(neutral and stable atmospheres)} \tag{5}$$

$$U_{\star} = \frac{\sigma_U}{3.0} \quad \text{(unstable atmospheres)} \tag{6}$$

where:

σ_U = standard deviation of wind speed along the average wind direction.

The denominator in Equation (6) is somewhat in doubt. Its actual value may range from 2 to about 5, with a median value of about 3.

The diabatic influence function, Φ, which should always have a positive value, depends on various parameters such as friction velocity and vertical heat flux.

Observations (Businger et al. 1971) have shown that

$$\Phi = 1 \qquad \text{(neutral atmospheres)} \qquad (7)$$

$$\Phi = 1 + 4.7Z/L \qquad \text{(stable atmospheres)} \qquad (8)$$

$$\Phi = (1 - 15Z/L)^{-\frac{1}{4}} \qquad \text{(unstable atmospheres)} \qquad (9)$$

where L (m) is called the Monin-Obukhov length. It's value is given by:

$$L = \frac{-U_*^3 \; T \; \rho \; C_p}{k \; g \; Q_H} \qquad (10)$$

where:

T = atmospheric temperature

ρ = atmospheric density

C_p = specific heat at constant pressure

g = acceleration due to gravity

Q_H = sensible heat flux from the ground to the atmosphere

The negative sign and von Karman's constant were added for convenience. The quantity L is infinite when the heat flux is zero (neutral atmospheric conditions). It is negative during unstable conditions when heat flux is upward from the ground to the atmosphere. It is positive during stable conditions when the direction of heat flux is reversed.

The absolute value of L can be thought of as the depth of the mechanically mixed layer near the surface (Hanna et al. 1982). Values for L over grass fields similar to those near Ellerslie should be about -100 and 100 under slightly unstable and slightly stable conditions, respectively (Irwin 1979). It follows from (8) and (9) that at Z = 150 m, Φ should have values of about 8 and 0.45 for slightly stable and slightly unstable atmospheres, respectively. It should never be negative. These conculsions assume that the

surface stress layer for which (4) applies coincides with the mechanically mixed layer. There is some doubt concerning this assumption for values of L greater than about 50 m.

Under neutral atmospheric conditions, when $\Phi = 1$, Equation (4) integrates to give the log law:

$$\bar{U} = \frac{U_*}{0.4} \ln (Z/Z_0) \qquad (11)$$

where:

Z_0 = integration constant known as the roughness length.

Equation (11) can be easily manipulated to show that U_* is proportional to the average wind speed measured at a given height.

Many arguments have been constructed to derive Equation (11) in a manner which gives physical meaning to Z_0. The two most popular arguments are those based upon mixing length theory (Haltiner and Martin 1957) and dimensional analyses (Gifford 1968). The mixing length theory has been strongly criticized as being physically unreasonable (Stewart 1979). Results of dimensional arguments, however, have been more widely accepted. In consequence, values of Z_0 are associated with the height of surface roughness elements, such as buildings, trees or plant cover. According to Hanna et al. (1982), Z_0 will be an order of magnitude less than these surface features. For the rural Ellerslie site where there are clusters of trees, Z_0 should have a value of about 0.5 m (Pasquill 1974).

Use of equation (3) assumes that the wind gradient is inversely proportional to elevation. Sometimes it is assumed that the gradient is also directly proportional to wind speed. That is,

$$\frac{d\bar{U}}{dZ} = \frac{P\bar{U}}{Z} \qquad (12)$$

where P is a dimensionless proportionality coefficient. Equation (12) may be integrated to give the power law:

$$U_1 = U_2 \, (Z_1/Z_2)^P \tag{13}$$

where U_1 and U_2 are wind speeds at levels Z_1 and Z_2, respectively.

Average values and standard deviations of P, as calculated from winds at the 10- and 60-m levels, have been found for rolling terrain to be about 0.10, 0.18 and 0.30 for unstable, neutral, and slightly stable atmospheres, respectively (Touma 1977). Standard deviations of P for these stability conditions are about 0.15, 0.13 and 0.17, respectively. Application of equations (11) and (13) show that the range of Z_0 needed to correspond to the observed standard deviation of P for neutral condition must cover several orders of magnitude.

A comparison between (4) and (12) shows:

$$\Phi = kP \frac{\bar{U}}{U_*} \tag{14}$$

Values of Φ can therefore be estimated from a knowledge of U_* and P.

2.1.2 Turbulence Parameters

Turbulence levels are indicated by standard deviations of longitudinal, lateral, and vertical wind speeds (σ_U, σ_V, σ_W). Measurements of turbulence intensities are given by the ratios of these standard deviations to wind speed (i.e., σ_U/U, σ_V/U, σ_W/U). Over relatively flat terrain, both turbulence levels and turbulence intensities should increase with decreasing stability. It has been found that under neutral atmospheric conditions $\sigma_V/\sigma_U = 0.75$ and $\sigma_W/\sigma_U = 0.50$ (Counihan 1975). Longitudinal intensities were found to be within the range:

$$0.12 \leqq \frac{\sigma_U}{U} \leqq 0.35 \tag{15}$$

The corresponding values for the lateral and vertical components can be derived from a knowledge of their ratios:

$$0.09 \leqq \frac{\sigma_V}{U} \leqq 0.26 \tag{16}$$

$$0.06 \leqq \frac{\sigma_W}{U} \leqq 0.175 \tag{17}$$

Turbulent wind fluctuations will change with wind speed. Evidence indicates that the horizontal components of turbulence (σ_U, σ_V) will decrease as speed increases (Leahey and Halitsky 1973; Leahey 1974; Pasquill 1974). Conclusions based on the observed behaviour of the vertical component of turbulence (σ_W) are ambiguous. There are indications that it will tend to either increase (Pasquill 1974) or decrease (Leahey 1974) with wind speed. There is, at present, no explanation for this contradictory evidence.

2.2 SPIRAL LAYER

Within the spiral layer, turbulence and wind direction change with height.

2.2.1 Vertical Variation in Wind Velocities

As previously mentioned, wind characteristics in the spiral layer depend not only upon frictional influences but also upon forces associated with Coriolis and surface pressure gradients. In consequence wind direction, which tends to be constant in the surface layer, changes with height. It becomes necessary, therefore, to consider two components of wind velocity. These are traditionally components parallel and perpendicular to the surface wind. Many attempts have been made to theoretically explain how each component should vary with height. Equations are usually complex, with allowances made for heat fluxes and geostrophic winds. These attempts have not enjoyed much success (Stewart 1979). It is clear, however, that wind tends to veer (turn clockwise) with increasing height. The extent of turning increases with stability and decreases with increasing wind speeds.

There have been many attempts to predict the variation of wind speed in the spiral layer. Perhaps some of the better known results are those of Wyngaard et al. (1974). They have presented results of theoretical calculations which give values of $U_0/U_\star$ and $V_0/U_\star$ as functions of $Zf/U_\star$ under neutral atmospheric conditions. The parameters U_0 and V_0 are components parallel and perpendicular, respectively, to the surface wind, and f is the Coriolis parameter (1.17×10^{-4} radians s^{-1} for Ellerslie). Results reported by Wyngaard et al. show, for example, that wind direction between the surface and 250 m should veer by about 1, 3, and 6 degrees for $U_\star$ values of 1.0, 0.5, and 0.2 m s^{-1}, respectively. The maximum predicted veer, regardless of height or $U_\star$ value, is about 10°. Typical observed values of veering between the surface and 1000 m for neutral atmospheric conditions are about 20 degrees (Smith 1973). Observed veerings over the same height interval for unstable and stable conditions are about 10 and 40 degrees, respectively.

The logarithmic wind profile given in Equation (11) was initially derived for wind speeds in the surface stress layer. Subsequent theoretical and observational studies have shown that this equation may have applicability to winds within the spiral layer (Carl et al. 1973; Tennekes 1973).

2.2.2 Turbulence Parameters

Vertical variations in atmospheric turbulence are very dependent upon stability. A description of these variations is given by Hanna et al. (1982)

Turbulence under stable situations should theoretically decrease linearly with height, reaching a value of zero at the top of the mixed layer. The height of this layer will be about 100 U_{10} where U_{10} is the 10-m wind speed (Benkley and Schulman 1979). At Ellerslie, under stable atmospheric conditions U_{10} is typically less than about 2 m s^{-1}. As mixing depths should therefore be less than about 200 m, turbulence should often drop to near zero within the 500-m range of the Doppler radar.

Under neutral atmospheric conditions turbulence should theoretically decrease exponentially with height. Thus,

$$\frac{\sigma_U}{U_*} = 2.0 \exp(-3\, Zf/U_*) \tag{18}$$

$$\frac{\sigma_V}{U_*} = 1.3 \exp(-2\, Zf/U_*) \tag{19}$$

$$\frac{\sigma_W}{U_*} = 1.3 \exp(-2\, Zf/U_*) \tag{20}$$

Equations (18), (19), and (20) show that the longitudinal component of turbulence should decrease with height more rapidly than the transverse and vertical components.

The relative madnitude of σ_U and σ_V near the ground (i.e. $Z \sim 0$) as given in (18) and (19) is supported by many observational studies (Pasquill (1974), Counihan (1975), Binkowski (1978), Panofsky and Dutton (1984)). All of the above referenced studies in contrast to equations (19) and (20) show, however, that σ_V is not equal to but is larger than σ_W. An exceptional study was that of Weber et al. (1975) which showed that σ_V was less than σ_W. Their equations for σ_V and σ_W are as follows:

$$\frac{\sigma_V}{U} = -1.75 - 2.35 \ln(fZ/U_*) \tag{21}$$

$$\frac{\sigma_W}{U} = -5.9 - 3.8 \ln(fZ/U_*) \tag{22}$$

As (21) and (22) indicate, σ_w/σ_V was found to be greater than unity near the ground and then to gradually decrease with height.

During unstable situations, horizontal components of turbulence, σ_U and σ_V, are theoretically independent of height within the mixing layer. The vertical component of turbulence, σ_W, however, has a maximum about midway in the layer. The depth of this

layer varies with season. Maximum afternoon values in the Ellerslie area are about 1550, 1900, 900, and 300 m for spring, summer, autumn, and winter, respectively. These values are based on information presented by Portelli (1977).

It is possible to make only general statements as to the expected behaviour of turbulence intensities. The horizontal components (σ_V/U, σ_U/U) should decrease with height for all stabilities. The vertical component (σ_W/U) should increase with height in unstable situations but decrease for neutral and stable situations (Hanna et al. 1982).

3. RESULTS

3.1 INSTRUMENT OPERATING EFFICIENCY

Doppler radar data were evaluated for stable, neutral, and unstable atmospheres. Vertical temperature gradients from the Doppler radar site were not available for this study. Reasonable assumptions had to be made. Stable and unstable atmospheres were consequently associated with night and daytime hours, respectively. Transition periods associated with neutral atmospheric situations were assumed to occur between three and four hours after sunrise, and between one and two hours before sunset. These assumptions were based upon time of breakup and formation of the nocturnal inversion, as shown by temperature data collected by Alberta Environment with an instrumented 92-m tower at Sherwood Park, near Edmonton. A total of 173 hours of neutral conditions were also associated with periods characterized by wind speeds at the 10-m level in excess of 7 m s^{-1}.

Table 1 shows the number of hours of available data according to level and stability class. For example, 679 hours of horizontal wind speed data are available for the 400-m level under neutral atmospheric conditions. This represents about 71 percent of all possible hours during neutral conditions. Winds from the 10 and 20 m levels were obtained from tower mounted anemometers. It is immediately apparent that reporting efficiency decreases with height. This decrease is due to attenuation of the return Doppler signal with distance. Efficiency at the higher levels is greater with unstable atmospheric conditions for all parameters except vertical velocity and its standard deviation.

3.2 EVALUATION OF DATA QUALITY

A cursory examination of Doppler acoustic radar data showed that information from the lower levels might not be reliable. Data collected at lower levels were therefore closely evaluated by comparison with information available from the 20-m level of the meteorological tower. It is recognized that the tower information is collected at a precise elevation, while the Doppler radar data

Table 1. Number of hours of all observed parameters by atmospheric stability. Observed frequencies as percentages of total time for each stability class are in parentheses.

Parameter	Level (m)	Atmospheric Stability					
		Stable		Neutral		Unstable	
Horizontal Speed (U)	10[a]	5236	(97)	943	(98)	1880	(97)
	20[a]	5272	(98)	950	(99)	1895	(98)
	50	5243	(98)	911	(95)	1898	(98)
	100	5247	(98)	796	(83)	1836	(95)
	150	5255	(98)	890	(93)	1914	(99)
	200	5304	(99)	907	(94)	1927	(99)
	250	5133	(95)	895	(93)	1923	(99)
	300	4944	(92)	851	(89)	1890	(97)
	350	4556	(85)	776	(81)	1852	(95)
	400	4000	(74)	679	(71)	1748	(90)
	450	3278	(61)	552	(57)	1595	(82)
	500	2280	(42)	395	(41)	1289	(66)
Standard Deviation of Horizontal Speed (σ_U)	50	5228	(97)	890	(93)	1894	(98)
	100	5222	(97)	735	(76)	1785	(92)
	150	5171	(96)	860	(89)	1899	(98)
	200	5282	(98)	880	(92)	1919	(99)
	250	5027	(93)	865	(90)	1910	(98)
	300	4766	(89)	813	(85)	1865	(96)
	350	4299	(80)	719	(75)	1812	(93)
	400	3684	(69)	608	(63)	1682	(87)
	450	2908	(54)	467	(49)	1486	(77)
	500	1899	(35)	319	(33)	1159	(60)
Direction (θ)	10	5232	(97)	943	(98)	1880	(97)
	20	5140	(96)	912	(95)	1866	(96)
	50	5244	(98)	911	(95)	1898	(98)
	100	5247	(98)	796	(83)	1836	(95)
	150	5255	(98)	890	(93)	1914	(99)
	200	5304	(99)	907	(94)	1927	(99)
	250	5133	(95)	895	(93)	1923	(99)
	300	4944	(92)	851	(89)	1890	(97)
	350	4556	(85)	776	(81)	1852	(95)
	400	4000	(74)	679	(71)	1748	(90)
	450	3278	(61)	552	(57)	1595	(82)
	500	2280	(42)	395	(41)	1289	(66)

continued...

Table 1. Concluded.

Parameter	Level	Atmospheric Stability					
		Stable		Neutral		Unstable	
Standard Deviation of Wind Direction (σ_θ)	50	4483	(83)	741	(77)	1430	(74)
	100	4122	(77)	646	(67)	1667	(86)
	150	5032	(94)	855	(89)	1894	(98)
	200	5102	(95)	869	(90)	1912	(98)
	250	4971	(92)	863	(90)	1907	(98)
	300	4739	(88)	813	(85)	1858	(96)
	350	4274	(79)	718	(75)	1810	(93)
	400	3661	(68)	609	(63)	1678	(86)
	450	2873	(53)	467	(49)	1484	(76)
	500	1879	(35)	318	(33)	1157	(60)
Vertical Speed (W)	50	1	(0)	0	(0)	0	(0)
	100	4884	(91)	695	(72)	1022	(53)
	150	4882	(91)	694	(72)	1021	(53)
	200	4879	(91)	693	(72)	1018	(52)
	250	4846	(90)	691	(72)	1015	(52)
	300	4736	(88)	675	(70)	1006	(52)
	350	4439	(83)	638	(66)	986	(51)
	400	4031	(75)	586	(61)	956	(49)
	450	3505	(65)	517	(54)	892	(46)
	500	2958	(55)	450	(47)	810	(42)
Standard Deviation of Vertical Speed (σ_W)	50	1	(0)	0	(0)	0	(0)
	100	4838	(90)	679	(71)	979	(50)
	150	4839	(90)	679	(71)	979	(50)
	200	4839	(90)	678	(71)	973	(50)
	250	4772	(89)	669	(70)	966	(50)
	300	4630	(86)	641	(67)	959	(49)
	350	4206	(78)	604	(63)	931	(48)
	400	3720	(69)	530	(55)	878	(45)
	450	3124	(58)	450	(47)	800	(41)
	500	2576	(48)	365	(38)	691	(36)

[a] From anemometer data

are representative of conditions through 50-m atmospheric layers. Doppler wind speeds, however, can be directly compared to anemometer winds providing they can be assumed to vary linearly with height within the 50 m layers. Such an assumption should be reasonable at heights greater than 150 m.

It is also recognized that mean wind speeds as observed by the anemometers and Doppler radar are different. Doppler winds are vectorially averaged while anemometer winds are not. Results of the two averaging approaches, however, as previously discussed, should be very similar.

Quality of data was investigated by calculating correlation coefficients between data at various levels. It was reasoned that the coefficients should decrease with height. Thus, information at the 20-m level should be most highly correlated with data from the 50-m level, and less correlated with that from the 100-m level, and so on.

Table 2 presents correlation coefficients between wind speeds at various levels over the 12-month observational period. It indicates, for example, that the correlation coefficient between winds at the 20 and 150 m levels is 0.66. A study of Table 2 shows that the 20 m winds were more highly correlated with the 150 m winds than with those at either the 50- or 100-m levels. Wind speeds at the 50-m level correlate poorly with winds at all other levels. Speeds at the 100-m level correlate with those at 150 m only slightly better than do 20-m winds. The type of behaviour revealed in Table 2 suggests that reported winds for the 50- and 100-m levels are not reliable. This conclusion was further tested by studying wind rose patterns and variations of wind speeds with height.

Figure 1 presents wind roses for the 20- and 50-m levels. Winds at the higher level appear to reflect a veer of about 180 degrees in direction and greatly reduced speeds. Such behaviour cannot be explained in terms of known atmospheric phenomena. Figure 2 shows vertical variations in annual median wind speeds for profiles reaching up to 500 m. The solid line is the expected profile based upon a power law relation (Equation [13]) at a

Table 2. Linear correlation coefficients between wind speeds at indicated levels.

Height (m)	Height (m)						
	20	50	100	150	200	250	300
50	0.10						
100	0.54	0.39					
150	0.66	0.31	0.71				
200	0.63	0.35	0.71	0.86			
250	0.61	0.31	0.68	0.87	0.88		
300		0.33	0.65	0.85	0.88	0.94	
350			0.62	0.82	0.84	0.91	0.96
400				0.77	0.79	0.85	0.89
450					0.76	0.81	0.85
500						0.77	0.83

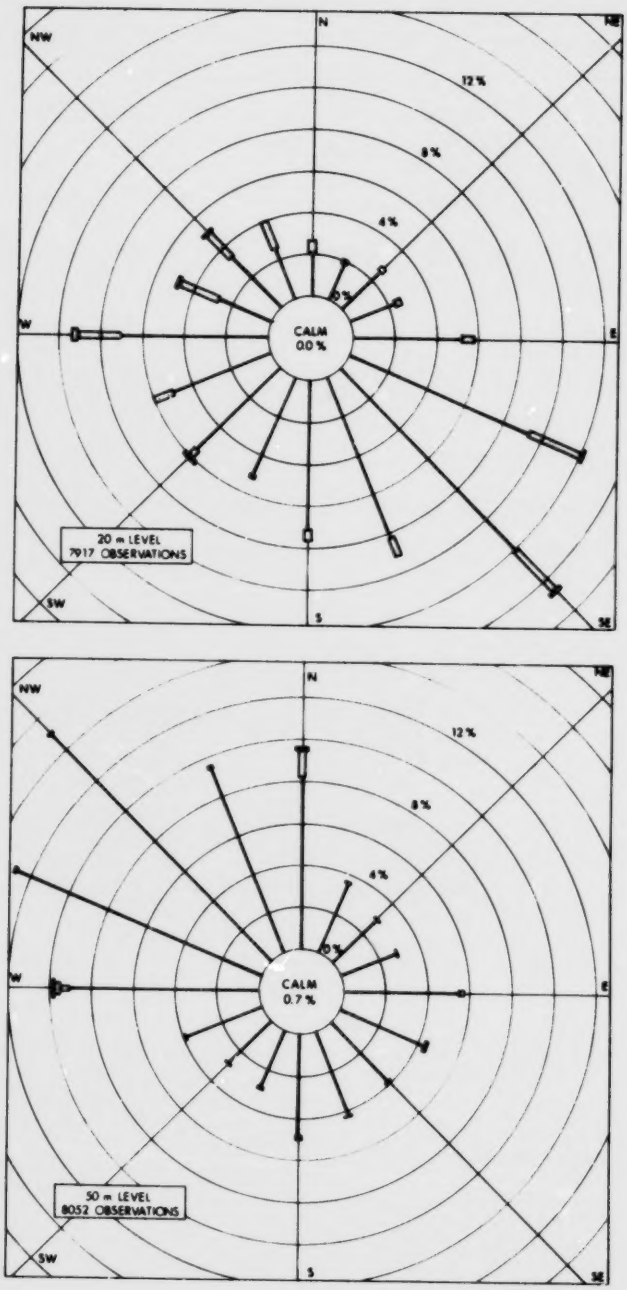

Figure 1. Wind roses at 20 and 50 m, based on all observed data.

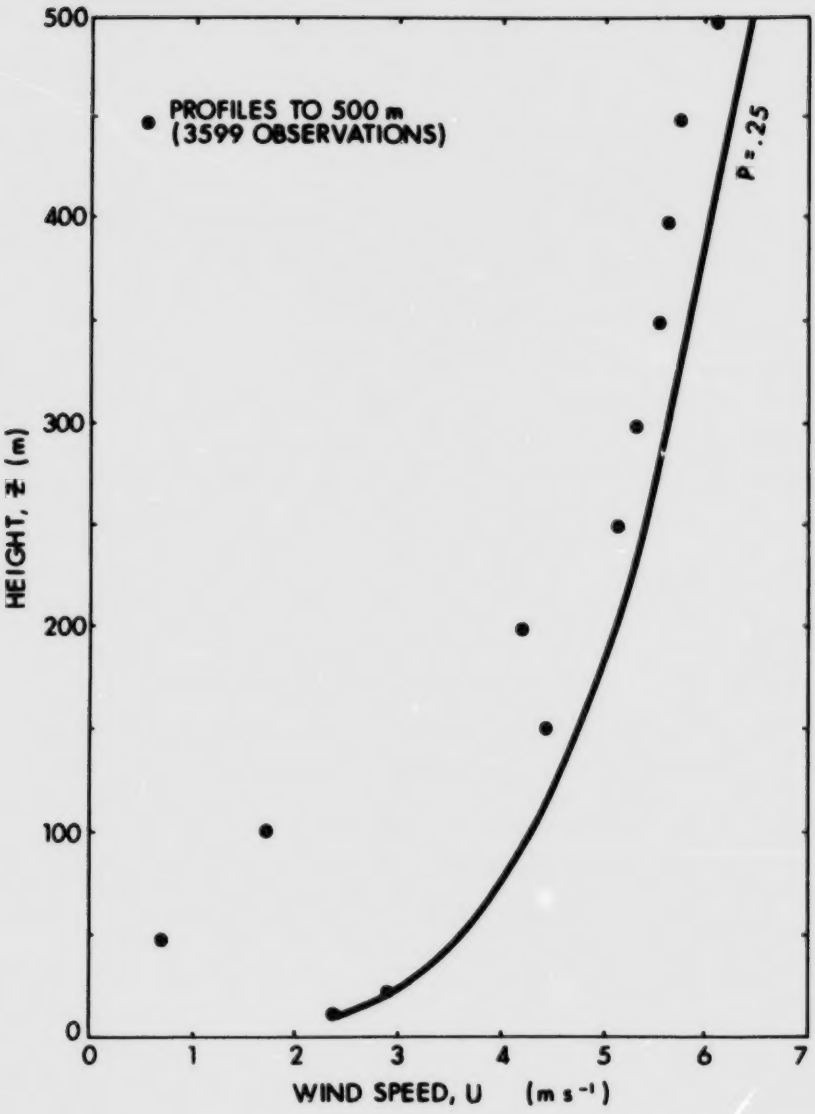

Figure 2. Median wind speeds as a function of height for all profiles reaching 500 m. A power law curve using an exponent of 0.25 (slightly stable atmosphere) is also shown.

reference level of 10 m with a valuefor P of 0.25, appropriate to slightly stable atmospheres which exist on average over the Ellerslie region. Reported wind speeds for the 50- and 100-m levels depart very markedly from expected behaviour. Of some interest is the fact that wind speeds at the 200-m level were less than those at the 150-m level.

It appears from the above analysis that Doppler winds reported for the 50- and 100-m levels are not acceptable. This is due to the classic radar phenomenon called ground clutter in which sidelobes of the transmitted beam reflect off the ground and nearby surface objects and bounce into receivers, thereby contaminating the data signal at low altitudes (Memo received 1985 April 24 from D. Netterville, Research Associate, Environmental Affairs, Syncrude Canada Ltd.).

Investigations were also undertaken to determine acceptability of data collected during December 1982 and January 1983, when the radar system was apparently having circuitry problems. Correlation coefficients between wind speeds at various levels were found to be similar to those shown in Table 2. Median changes in wind direction with height during stable conditions were compared with those observed over the year. Results of this comparison, presented in Figure 3, showed that directional changes during the December and January period were similar to those experienced at other times. It was concluded that data collected during the period of circuitry problems were acceptable.

3.3 VARIATION OF PARAMETERS AT SELECTED LEVELS

All wind and turbulence data were evaluated to assess their behaviour at specified levels.

Figure 4 compares wind roses at the 20-, 200-, 350- and 500-m levels. Light southeasterly winds were observed most frequently at the 20-m level. Observed wind patterns changed with height and at the 500-m level, winds were much stronger and predominantly from the northwest.

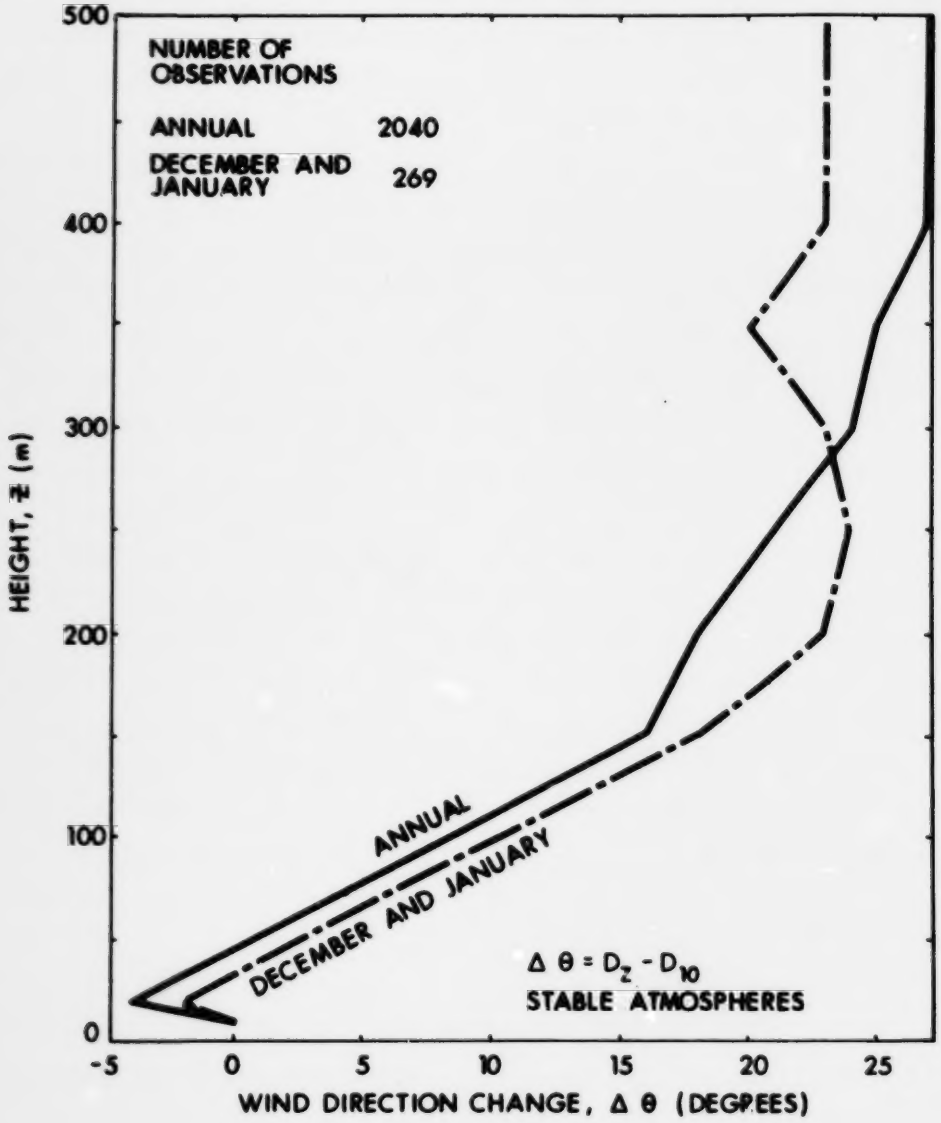

Figure 3. Median change in wind direction compared with that at 10 m as a function of height (stable conditions).

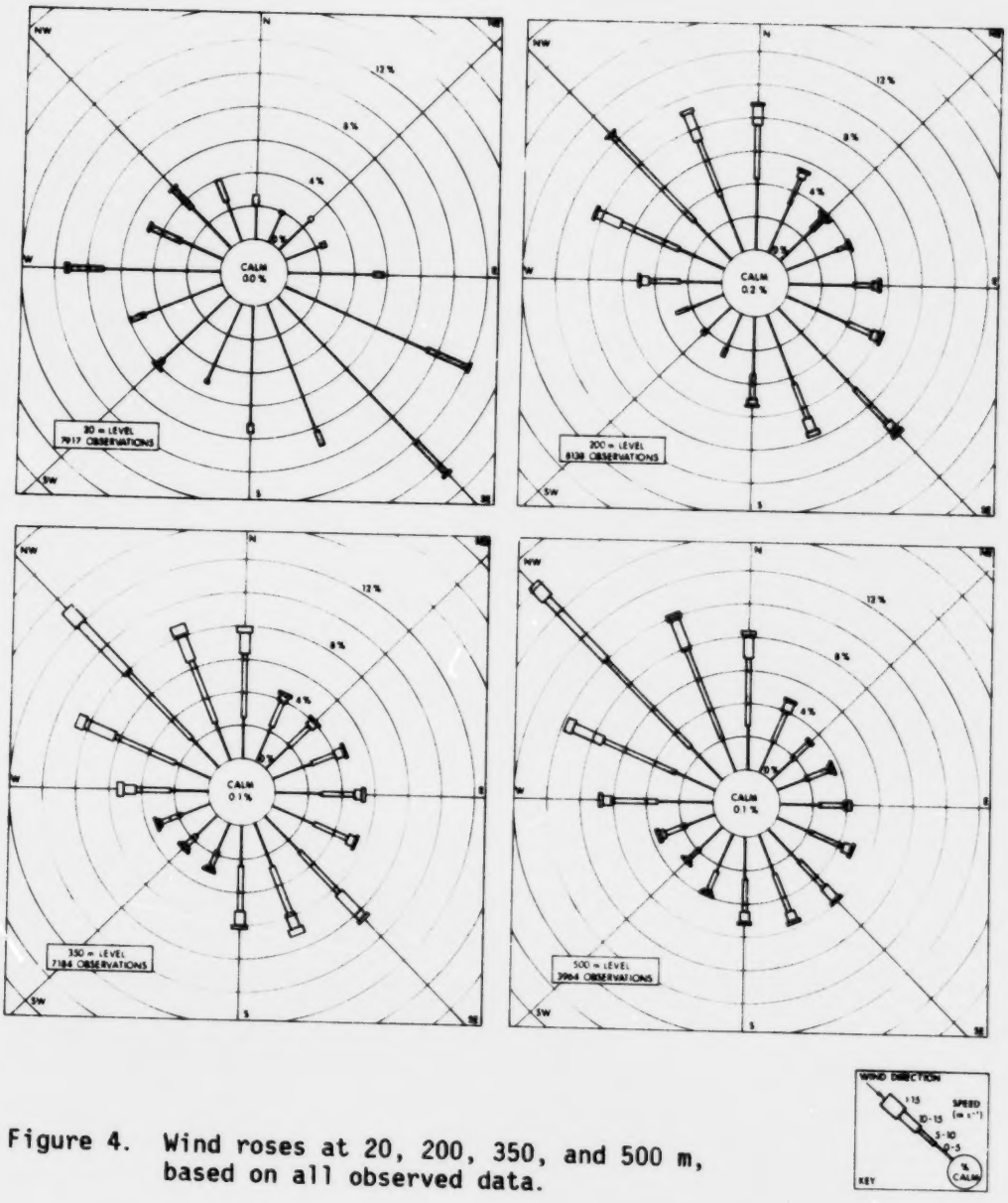

Figure 4. Wind roses at 20, 200, 350, and 500 m, based on all observed data.

Figure 5 shows the cumulative frequency distribution of horizontal wind speeds observed at the 20-, 200- and 350-m elevations. The distribution for 500 m is not shown because it was essentially the same as that for 350 m. As expected, wind speeds showed a marked tendency to increase with height. The one, five, and 10 percentile winds at 200 m are less than corresponding winds at 20 m.

The cumulative frequencies of vertical wind speeds observed at 200-, 350- and 500-m levels are shown in Figure 6. Observed magnitudes of both updrafts (positive W) and downdrafts (negative W) tended to increase with height. Median values of W were slightly positive (about 0.1 m s^{-1}).

Figure 7 presents cumulative frequency distributions of the longitudinal, transverse, and vertical components of turbulence as observed at the 350 m level. The ordinate has a logarithmic scale. Distributions approximate straight lines, indicating that they are nearly lognormal. Ranges of values for the standard deviations exceeded an order of magnitude. Longitudinal and transverse components tended to have similar values. Medians for σ_U, σ_V, and σ_W were 1.2, 1.4, and 0.3 ms^{-1}, respectively. Corresponding standard deviations were 1.55, 1.73 and 0.26 ms^{-1}. Observed behaviour of σ_U, σ_V, and σ_W at levels of the atmosphere other than at 350 m also demonstrated lognormal distributions.

Turbulence components at the 150-m level were analyzed to determine if they were functions of 10-m wind velocity. Table 3 presents median values of σ_U, σ_V, and σ_W for 16 wind directions. There was a tendency for greater turbulence to be associated with northwesterly winds. The tendency was not very pronounced. Figure 8 shows median values of the turbulence parameters for various wind speed classes. There was a very noticeable tendency for strong horizontal turbulence (σ_U, σ_V) to be associated with high winds. This was surprising in view of findings relating to the opposite behaviour of horizontal turbulence as observed near ground level. Levels of vertical turbulence, appeared to be virtually independent of wind speed.

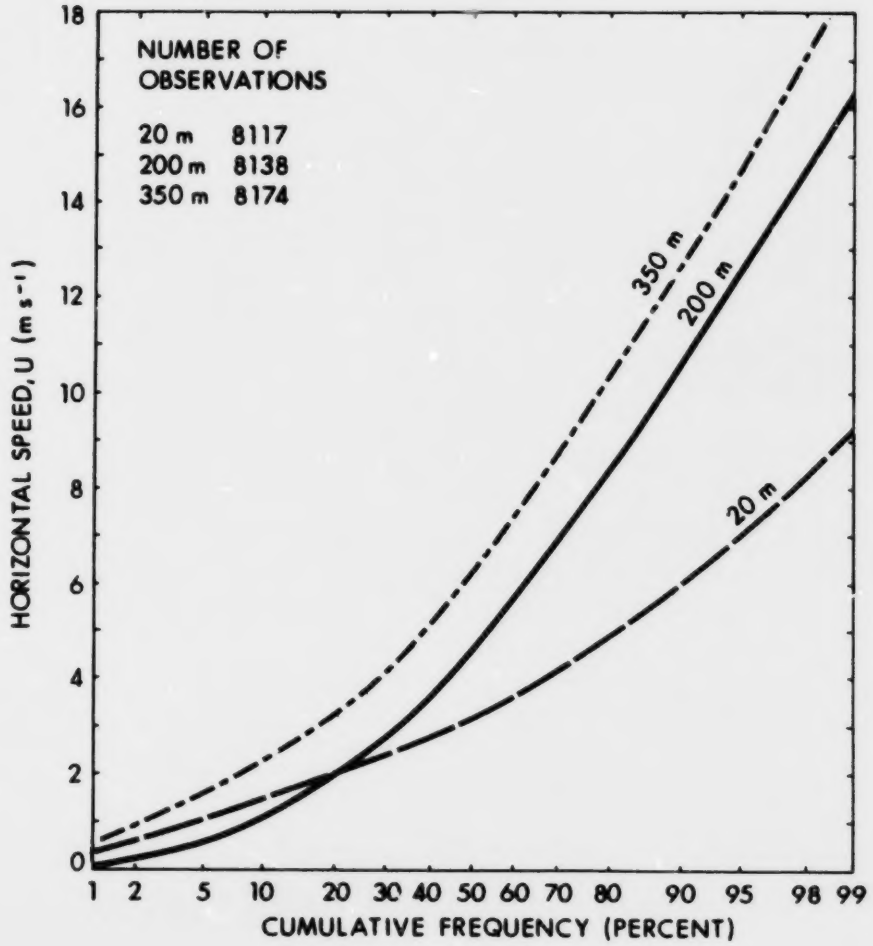

Figure 5. Frequency distribution of horizontal wind speeds at 20, 200, and 350 m, based on all observed data.

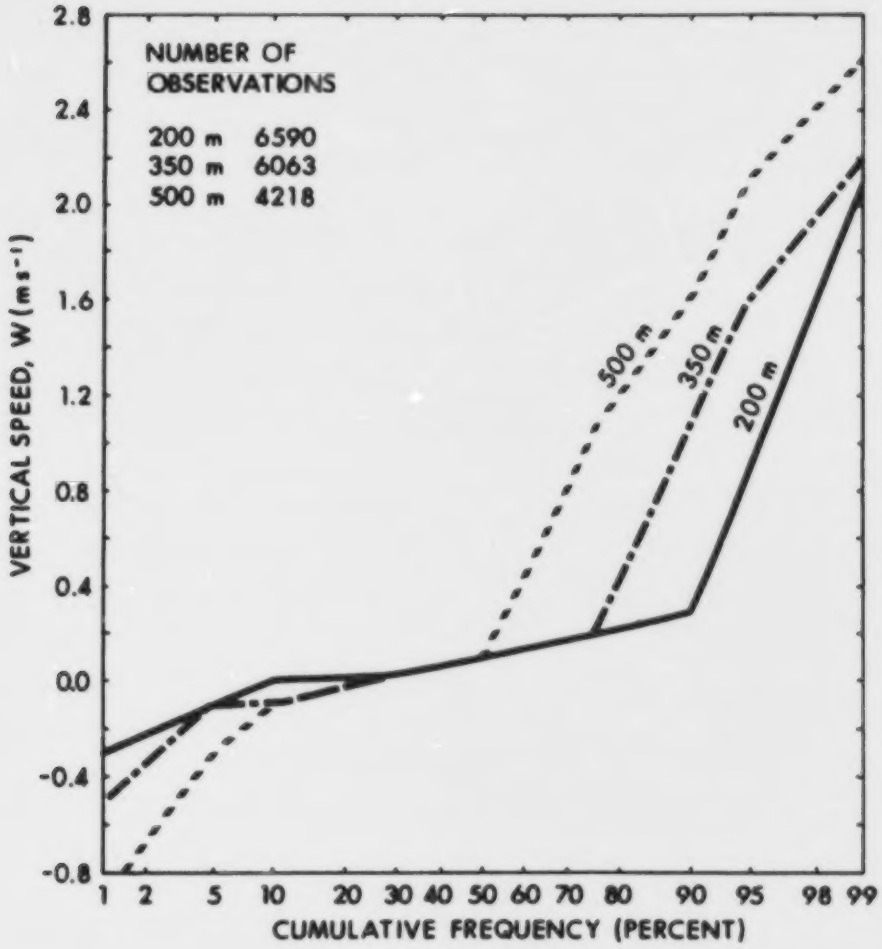

Figure 6. Frequency distribution of vertical wind speeds at 200, 350, and 500 m, based on all observed data.

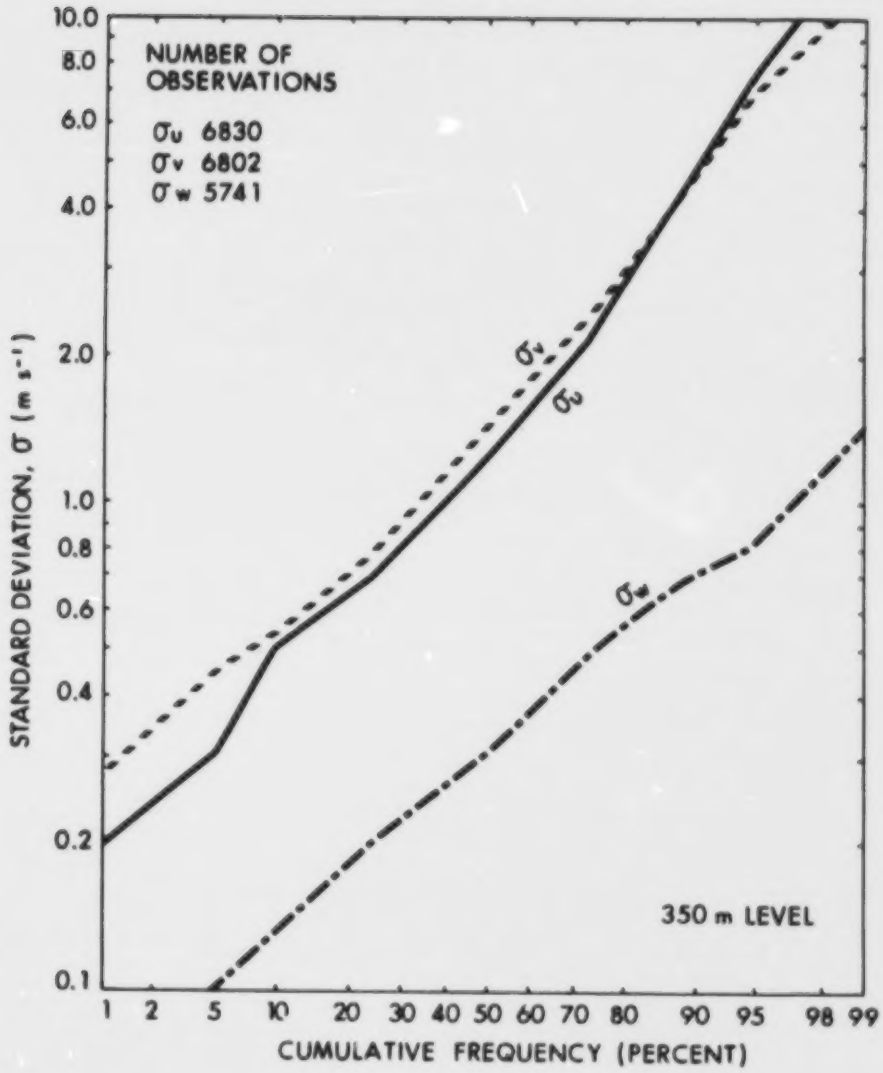

Figure 7. Frequency distribution of longitudinal, transverse, and vertical components of turbulence at 350 m.

Table 3. Median values of turbulence parameters at 150 m as a function of surface wind direction. Number of data, n, upon which medians are based is also shown.

Wind Direction	σ_U (m s^{-1})		σ_V (m s^{-1})		σ_W (m s^{-1})	
	median	n	median	n	median	n
NNE	0.78	214	0.92	213	0.48	148
NE	0.85	223	0.88	223	0.40	181
ENE	0.92	257	0.75	255	0.47	202
E	0.76	247	0.80	243	0.47	163
ESE	0.94	562	0.94	551	0.49	466
SE	0.98	1335	0.98	1307	0.53	1176
SSE	0.78	858	0.92	830	0.50	700
S	0.94	637	0.85	610	0.44	565
SSW	0.94	393	0.97	381	0.47	346
SW	0.90	474	1.02	467	0.55	429
WSW	0.92	415	1.00	406	0.57	349
W	0.87	458	1.10	454	0.61	375
WNW	1.02	456	1.20	451	0.57	341
NW	0.97	476	1.15	473	0.53	330
NNW	0.97	338	1.15	336	0.46	250
N	0.80	370	0.90	368	0.44	275

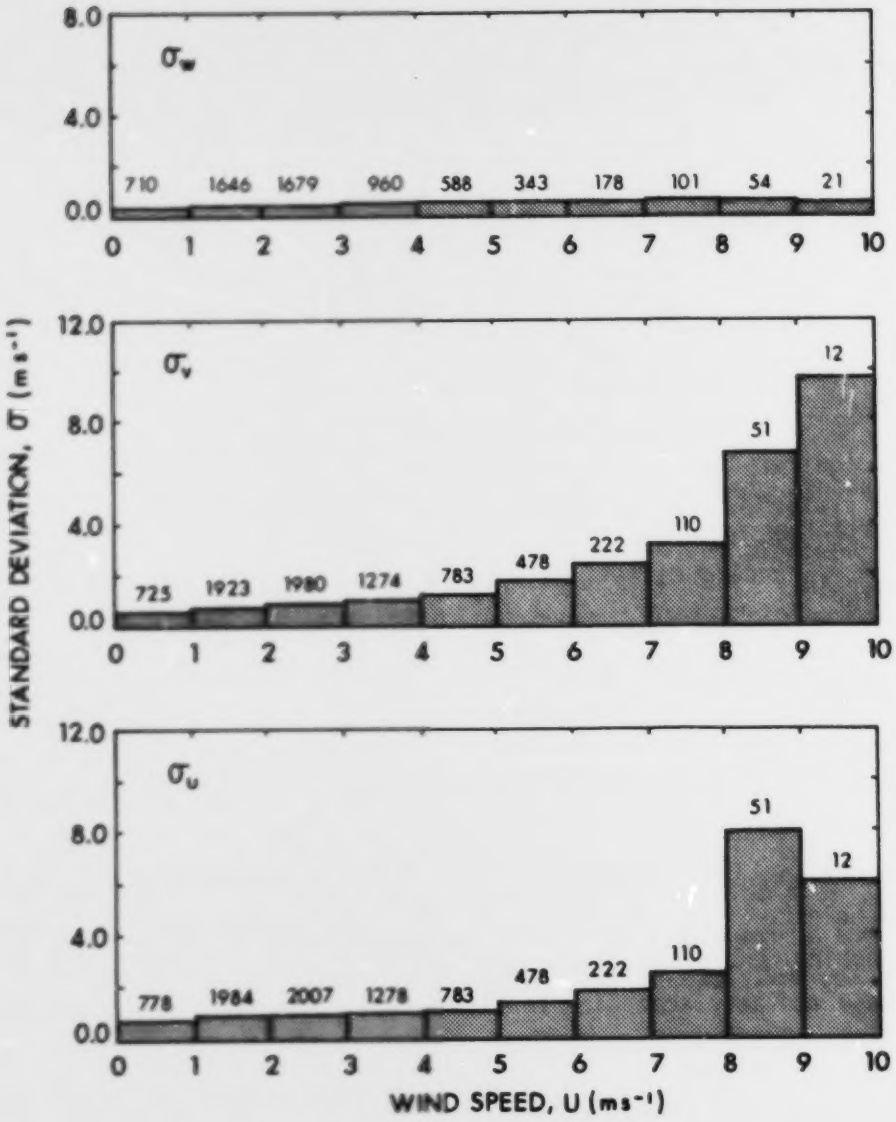

Figure 8. Median values of turbulence parameters at 150 m as a function of wind speed at 10 m. The number of observations on which medians are based is also shown.

3.4 VERTICAL VARIATIONS IN MEDIAN WINDS

Doppler radar information was analyzed to determine vertical variations in horizontal wind speed and turbulence.

Conclusions concerning vertical variations in atmospheric phenomena should apply to typical conditions. Therefore median values rather than averages were chosen as the basis for comparison. Median values of the various parameters should be more representative because they are less influenced by atypical phenomena such as thunderstorms or frontal activity.

Most of the generalizations concerning vertical variations were obtained from profiles which extended to 500 m. These longer profiles give correspondingly more information about vertical variations.

The Doppler radar gave hourly-averaged values for the standard deviation of wind direction (σ_θ) as well as standard deviations of the longitudinal and vertical wind components (σ_U, σ_W). Standard deviations of the transverse component of turbulence (σ_V) were obtained through the relation $\sigma_V = U\,\sigma_\theta$.

As shown in Table 1, Doppler radar soundings reached the 500-m level only about 40 percent of the time. Evaluations were made to try and assess the representativeness of data collected during times when Doppler radar information extended to this elevation. Median values of horizontal wind speed, power law exponent (Equation [13]), wind speed components, and the three components of turbulence were assessed at the 350-m level for all profiles reaching 350 m and then only for those reaching 500 m. Tables of these medians, according to season and stability category, are given in the appendix. They show that meteorological conditions associated with 500 m profiles were characterized by values of horizontal turbulence components and wind speeds of up to 30 percent less than those associated with profiles reaching only to 350 m. There were no noticeable differences in the vertical turbulence component or in the shape of the wind profile (i.e., P).

It is assumed in the following analyses that information from profiles extending to 500 m is representative of the atmosphere. This assumption seems reasonable in so far as a 30 percent difference in a given median is small when compared to the range of values upon which the median is based. These ranges, as illustrated in Figures 5, 6, and 7, exceed an order of magnitude.

3.4.1 Vertical Variations in Horizontal Wind Velocity

Wind data for the 500-m profiles were examined in order to assess the manner in which wind speeds and wind directions varied with height.

Values of the friction velocity, $U_\star$, were calculated, based on the longitudinal turbulence component, σ_U, observed at the 150-m level. Distributions of resulting $U_\star$, based on Equations (5) and (6), are given as a log plot in Figure 9. Median values are 0.37, 0.42, and 0.46 for unstable, stable, and neutral atmospheres, respectively. The distributions are nearly straight lines indicating that they may be approximated by lognormal functions.

Figure 10 shows a semi-log plot of median wind speeds as a function of height for neutral atmospheres. Values approximate a straight line, indicating a variation with log Z as predicted by Equation (8). The straight line fitted by least squares methods has a correlation coefficient of 0.97. From the slope and intercept of the line, values of $U_\star$ and Z_0 can be estimated as 0.40 m s^{-1} and 0.83 m, respectively. The wind speed at the 200-m level is appreciably less than might have been expected on the basis of the log law relation.

Individual values of $U_\star$ and Z_0 were estimated from each profile extending from 10 to 500 metres using Equation (11) with hourly averaged wind data and least square techniques. Only circumstances when wind speeds increased with height under neutral atmospheric situations were used for this analysis. Wind information collected by anemometer at 10 and 20 m were combined with information collected by Doppler radar at higher elevations. Values of $U_\star$

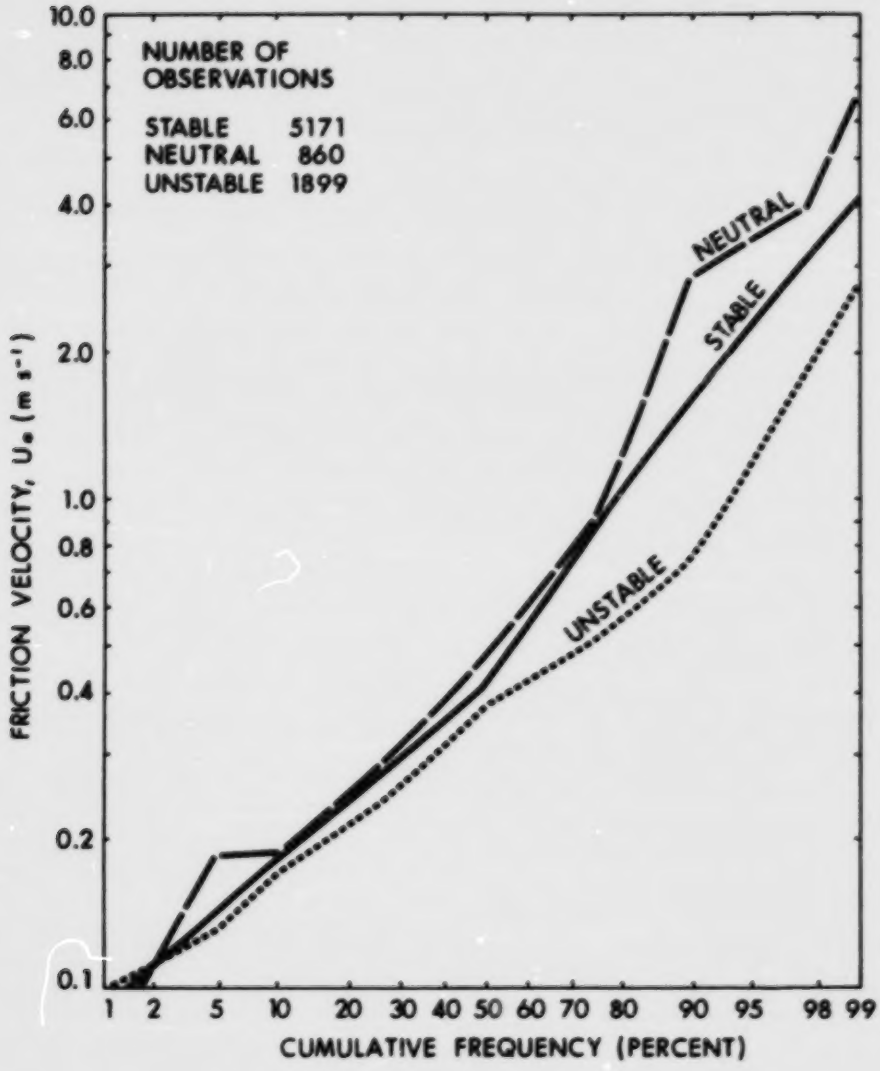

Figure 9. Frequency distribution of friction velocity, U_*, calculated from the longitudinal turbulence component, σ_U, at 150 m.

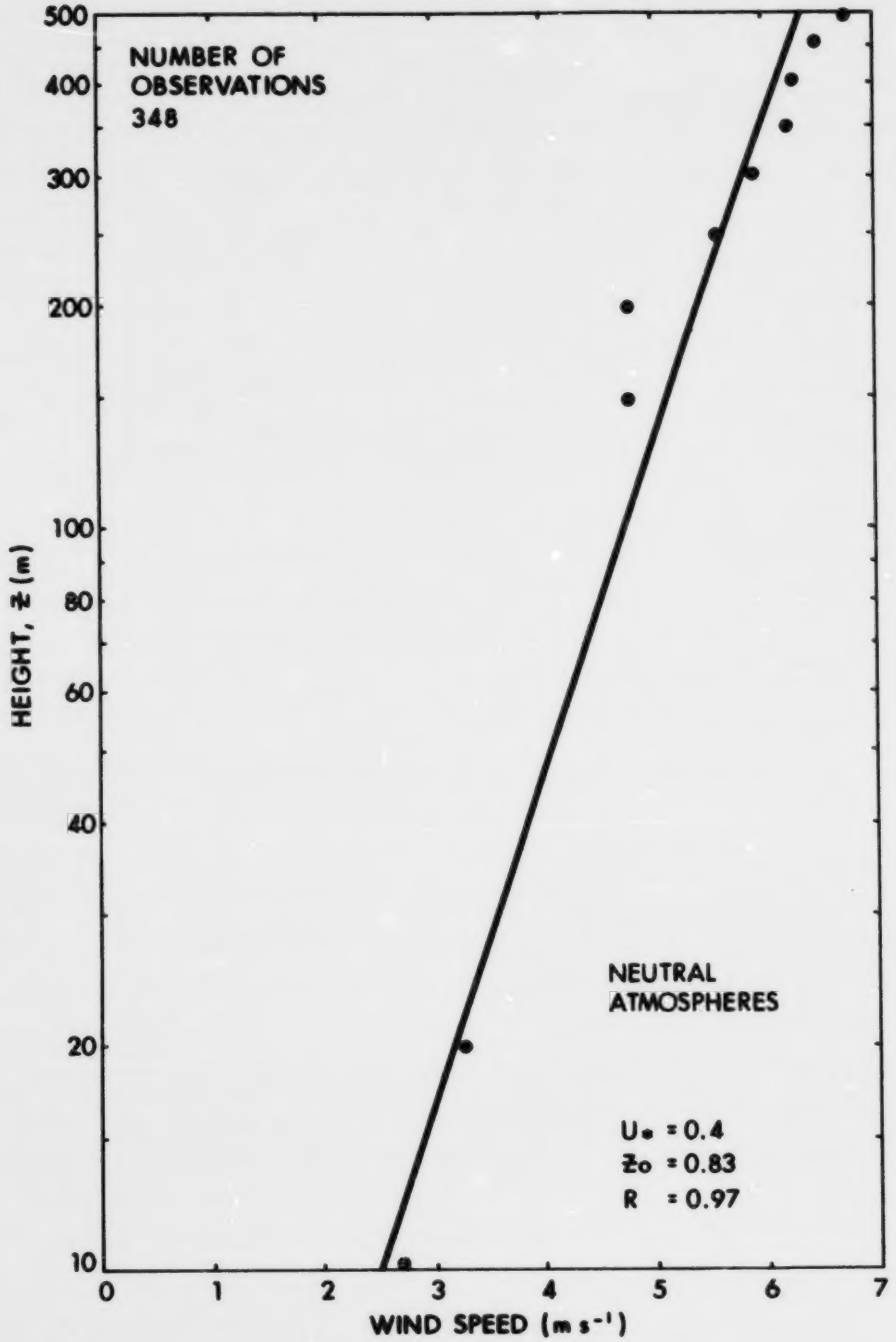

Figure 10. Median observed wind speeds as a function of height. A least squares regression line is also shown.

and Z_0 were also estimated using only Doppler wind data collected above 150 m. Table 4 presents statistical parameters relating to the log law as derived from wind data collected over two different elevation ranges. Medians and standard deviations (S.D.) of $U_\star$ and Z_0 derived from data extending from 10 to 500 m were much smaller than those derived only from data collected above 150 m. The smaller standard deviations suggest that the log law better explains wind behaviour near the ground than at elevations above 150 m. Such a finding would be consistent with surface layer theory.

Figure 11 shows a comparison between frequency distributions of $U_\star$ for neutral atmospheres estimated from both turbulence (Equation [5]) and from the 10 to 500 m wind profiles. In the turbulence method, values of $U_\star$ were based on σ_U observed at the 150 m level. Median $U_\star$ values of 0.45 and 0.35 ms^{-1} derived using the turbulence and profile methods, respectively, are comparable. The respective standard deviations of 1.3 and 0.3 were, however, appreciably different. Figure 12 illustrates frequency distributions of Z_0 calculated from 10 to 500 m wind data for each season. Values varied over three orders of magnitude.

Median values of the exponent P for the power law function (Equation [13]) were also calculated by least square techniques for each profile employed in deriving Z_0 and $U_\star$. Table 4 presents statistical parameters relating to P as derived from wind data collected over the two different elevation ranges. Values of P, as derived from data extending from 10 to 500 m were much smaller than those derived only from data collected above 150 m. The larger P values as obtained from 150-500 m data may reflect the fact that upper levels are more often the domain of stable thermal stratifications in which steep wind gradients are more common than is the case in the surface layer.

Calculations were performed to determine whether the log law function (Equation [11]) or the power law function (Equation [13]) gave better estimates of wind speed for neutral conditions. Calculations were based on 348 profiles which reached to 500 m.

Table 4. Variations of U_*, Z_o, P and correlation coefficients (R) as determined from wind data from 10 to 500 m and from 150 to 500 m

Parameter	Statistic	Elevation Range (m) 10 to 500	Elevation Range (m) 150 to 500
	n	348	319
U_*	median	0.35	0.84
	range	0.01 - 1.80	0.01 - 8.71
	S.D.	0.31	0.91
Z_o	median	0.33	14.7
	range	[a]0.000 - 16.3	0.000 - 172
	S.D.	3.0	36.8
log law	R	0.88	0.91
P	median	0.17	0.30
	range	0.01 - 0.74	0.02 - 4.14
	S.D.	0.12	0.39
power law	R	0.90	0.88

[a] Less than 0.0005

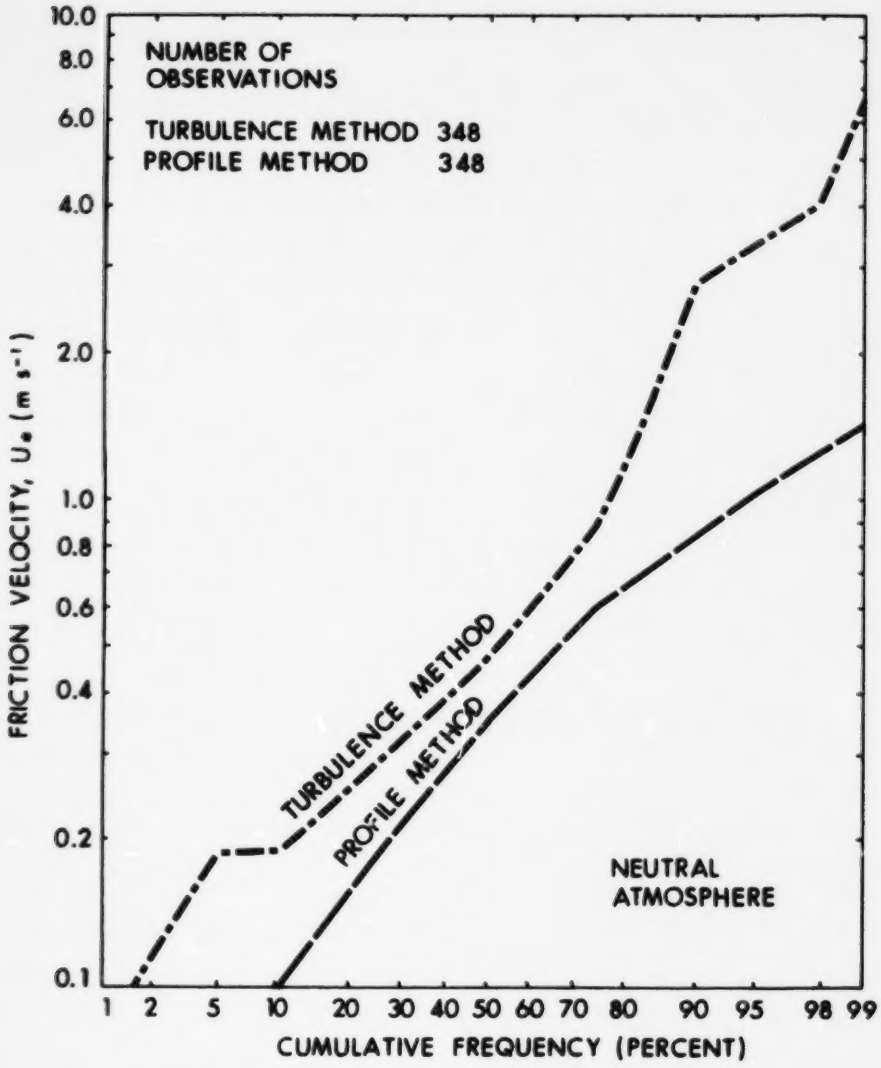

Figure 11. Frequency distributions of friction velocity for neutral conditions based on both turbulence and log profile relations.

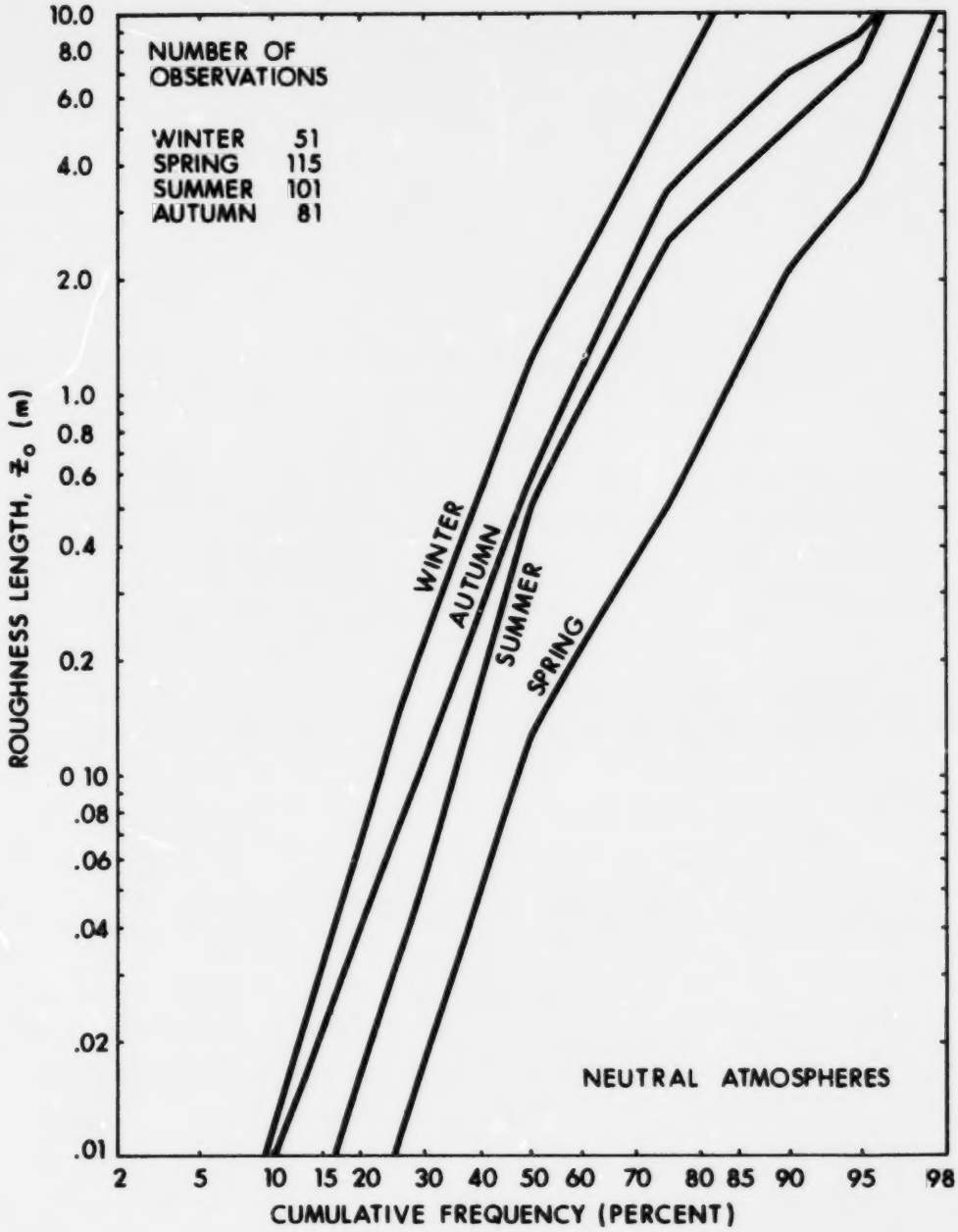

Figure 12. Frequency distributions of roughness lengths for each season.

Correlation coefficients were estimated for each profile from the equation:

$$R^2 = 1 - \frac{SE^2}{\sigma^2} \qquad (23)$$

where: R = correlation coefficient
SE = standard error of estimate
σ = standard deviation of sample

Table 4 shows that the correlation coefficients for log and power law wind profiles were about 0.89 regardless of data set.

Values of the exponent P, as calculated from all valid 10 to 500 m wind data are illustrated in Figure 13. Values varied from about -0.20 to about 0.80. Medians for unstable, neutral and stable atmospheric conditions were 0.10, 0.17 and 0.28, respectively. Negative values of P, indicating a tendency for wind speed to decrease with height, occurred about four, five and 12 percent of the time for stable, neutral and unstable conditions, respectively. Standard deviations for P for unstable, neutral and stable atmosphere were 0.11, 0.13 and 0.17, respectively.

Median differences in wind directions from 10-m values are shown in Figure 14 as a function of height. Changes occurred more rapidly near the ground and were largest under stable atmospheric situations. Figure 15 presents cumulative frequencies of wind direction changes between the 10 and 250 m levels. Direction changes increased with stability. Median values were about 5, 10, and 20 degrees for unstable, neutral, and stable atmospheres, respectively. About thirty percent of direction changes were negative, indicating a backing of wind with height. The lines for stable and neutral conditions in Figure 15 are approximately straight, indicating a tendency for direction changes to have a normal distribution.

Values of the diabatic influence function, Φ, for the 150 m level were evaluated using Equation (14), the power law exponent, P, as derived from 10 to 500 m wind data and values of U_* estimated from equations (5) and (6).

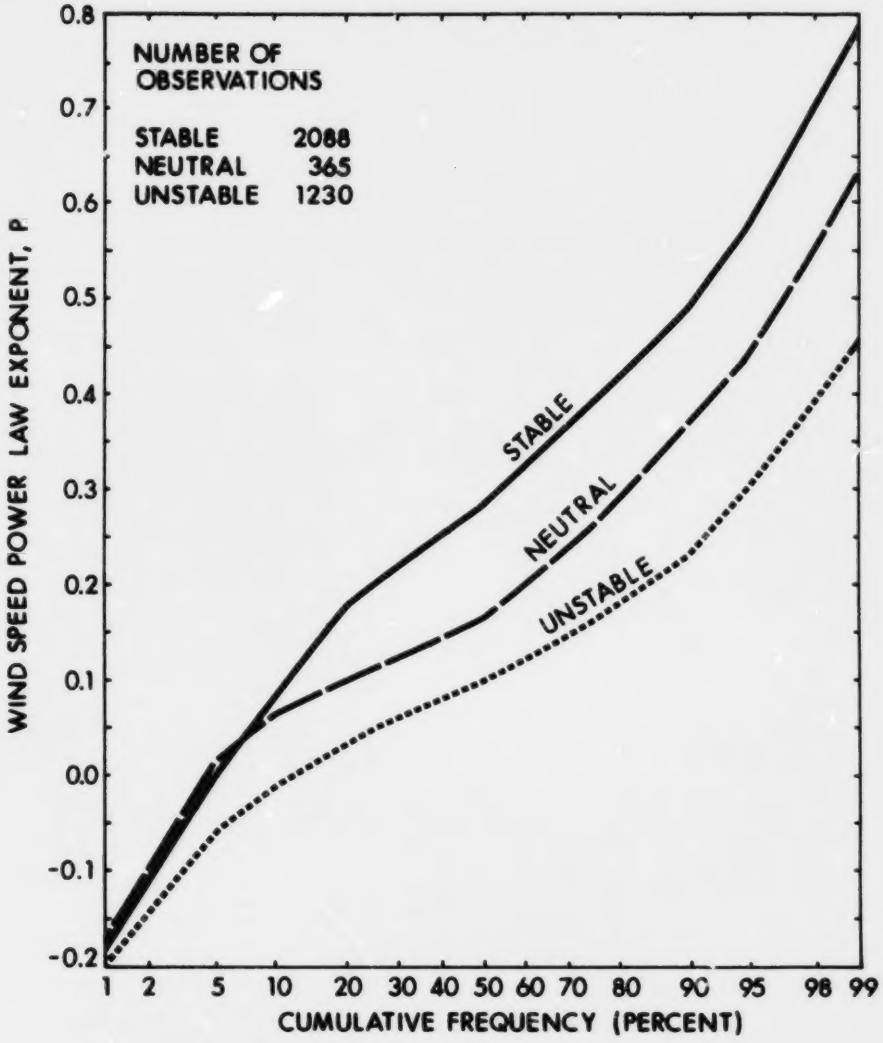

Figure 13. Frequency distribution of power law exponent, P.

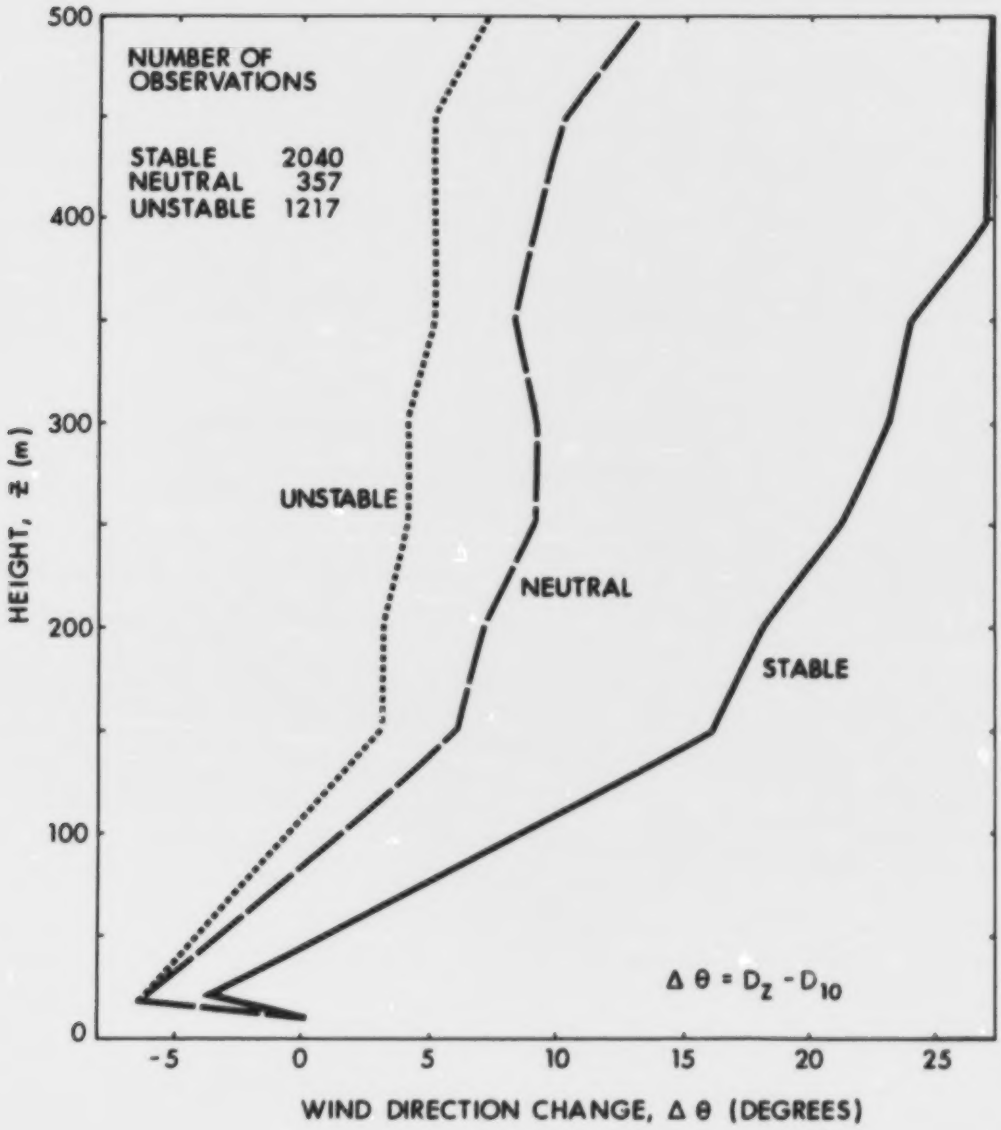

Figure 14. Median change in wind direction compared with that at 10 m as a function of height for different atmospheric stability conditions.

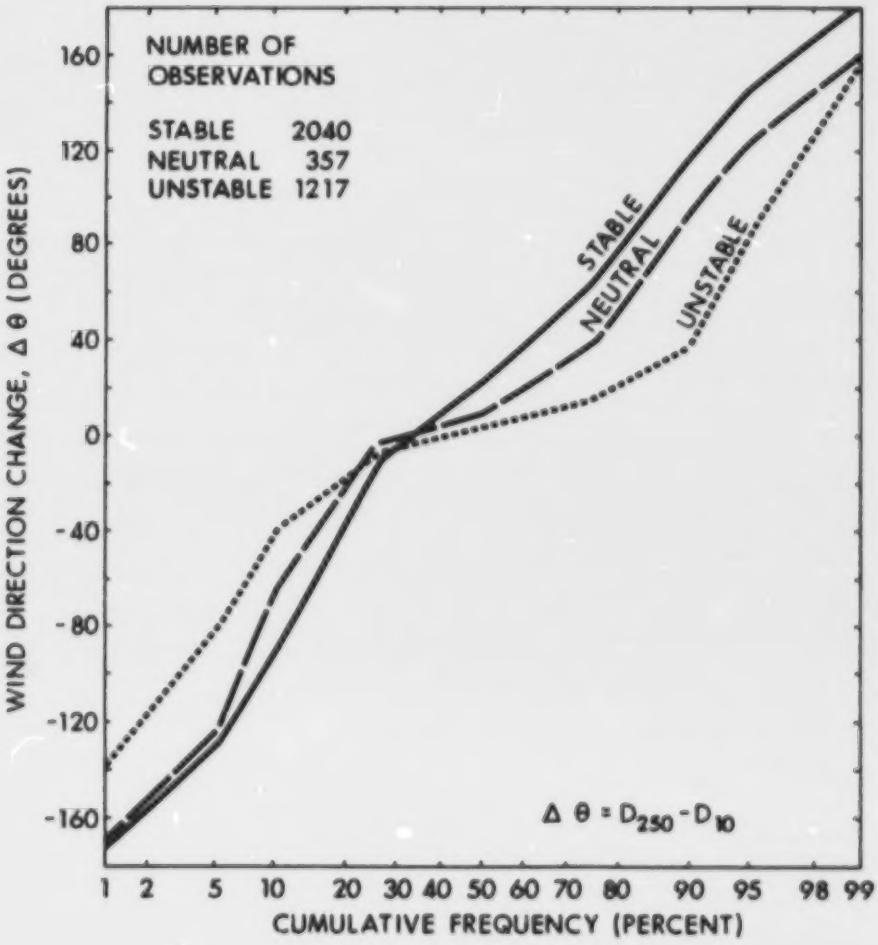

Figure 15. Frequency distribution of differences in wind direction between 250 and 10 m.

Figure 16 shows frequency distributions of Φ for unstable, neutral and stable atmospheres. Median values were about 0.40, 0.70, and 1.1, respectively. About 5 percent of Φ values were negative.

Horizontal winds were separated into two vector components: U_0 being parallel to the 10 m wind, and V_0 being perpendicular. Figure 17 shows a comparison between predicted (Wyngaard et al. 1974) and median observed values under neutral atmospheric conditions of V_0/U_0 as a function of Zf/U_* where the friction velocity is assumed to have a value of 0.4 m s^{-1}. The correlation coefficient R was calculated for the entire curve and then only for that portion of the curve which would not be contaminated by observational errors in the wind at 20 m. In both instances, the value of R was found to be equal to zero. There thus seems to be no direct correspondence between predicted and observed wind patterns.

3.4.2. Vertical Variations in Turbulence

Figure 18 shows a semi-log plot of vertical variations in medians of the longitudinal component of turbulence for stable and unstable atmospheres. Values of σ_U for stable conditions tended to have a maximum at 200 m. There was a tendency on this semi-log plot to increase linearly with height above 250 m. The same general tendencies are evident in the profile of median σ_U values associated with unstable atmospheres. The tendency for a maximum at 200 m is, however, much less pronounced.

An examination of median σ_U values for neutral atmospheres showed that they were very similar to those given in Figure 18 for stable atmospheres.

Figure 19 presents a semi-log plot of median σ_V and σ_W values as functions of height for stable atmospheres. Values of σ_V and σ_W tended to linearly increase and decrease respectively with height. Tendencies for σ_W to decrease incrementally with height are due to the fact that it was only measured to the nearest 0.1 m s^{-1}. Neither σ_V nor σ_W tended to behave in an anomalous fashion at 200 m. They therefore differed in this respect from σ_U. Further studies showed that σ_V and σ_W also tended to increase and decrease linearly, respectively, for both neutral and unstable atmospheres.

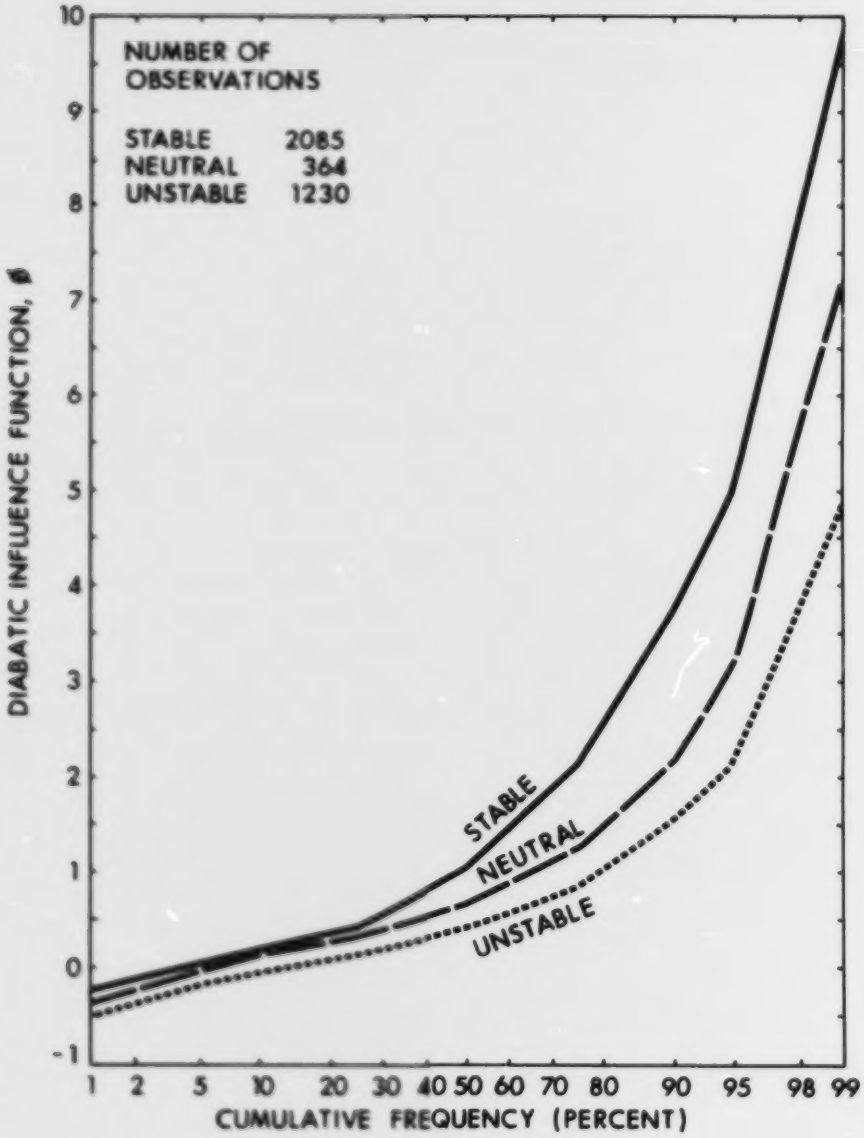

Figure 16. Frequency distributions of the diabatic influence function for the 150-m level.

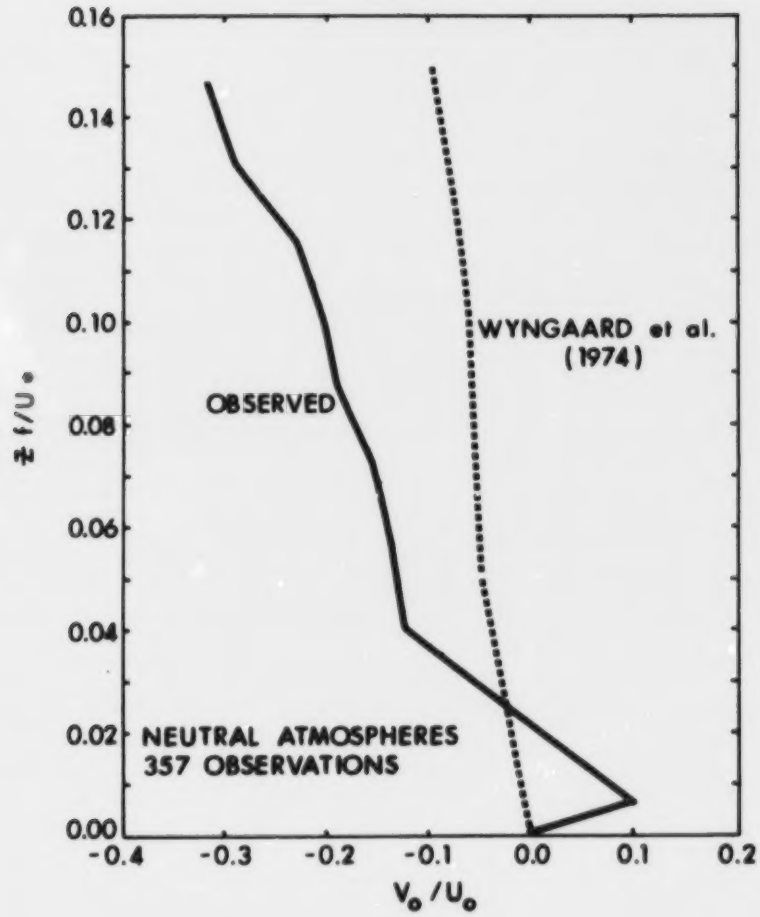

Figure 17. Comparison of predicted (Wyngaard et al. 1974) and observed values of V_o/U_o as a function of Zf/U_*. U_o is positive along the 10-m wind direction. V_o is positive clockwise, perpendicular to the 10-m wind direction.

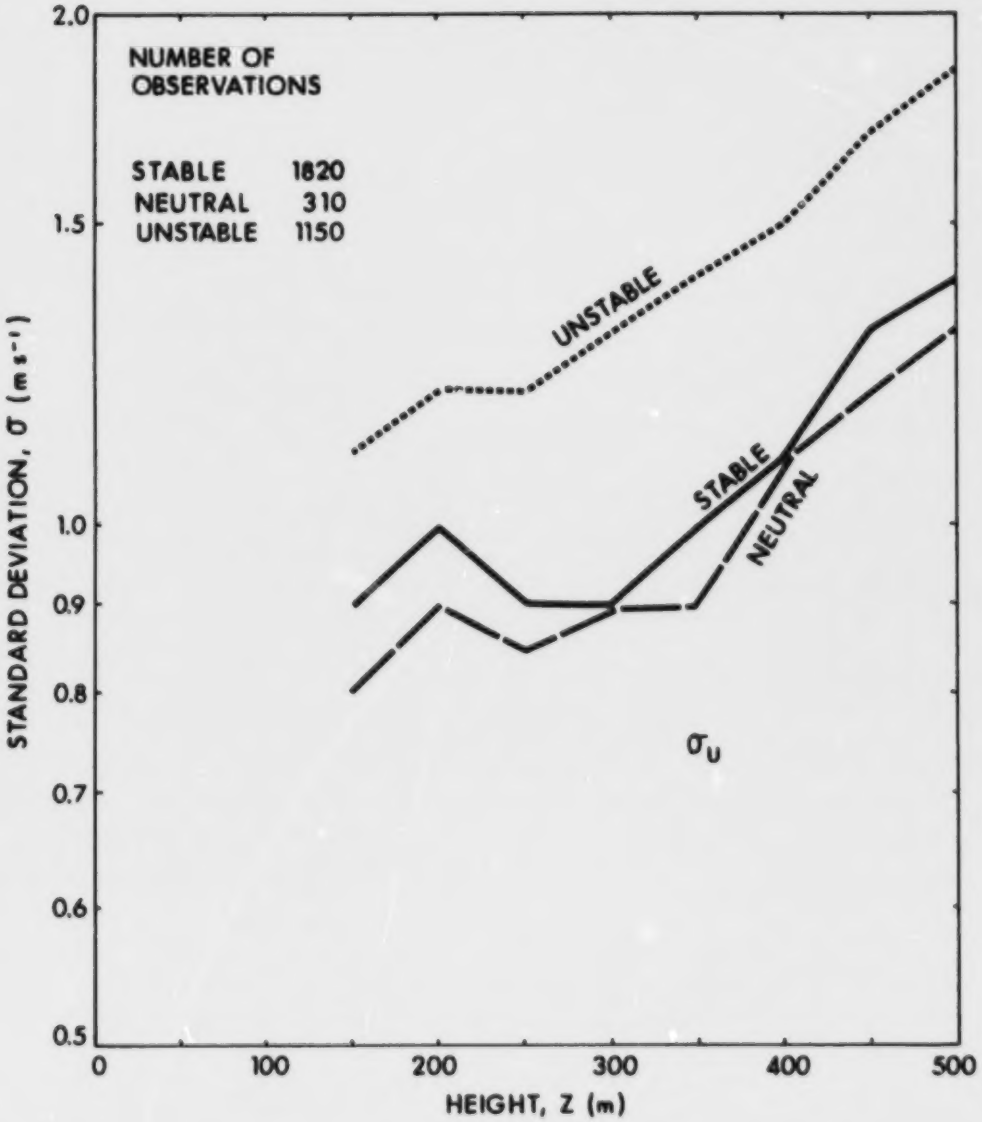

Figure 18. Median values of the longitudinal component of turbulence as a function of height.

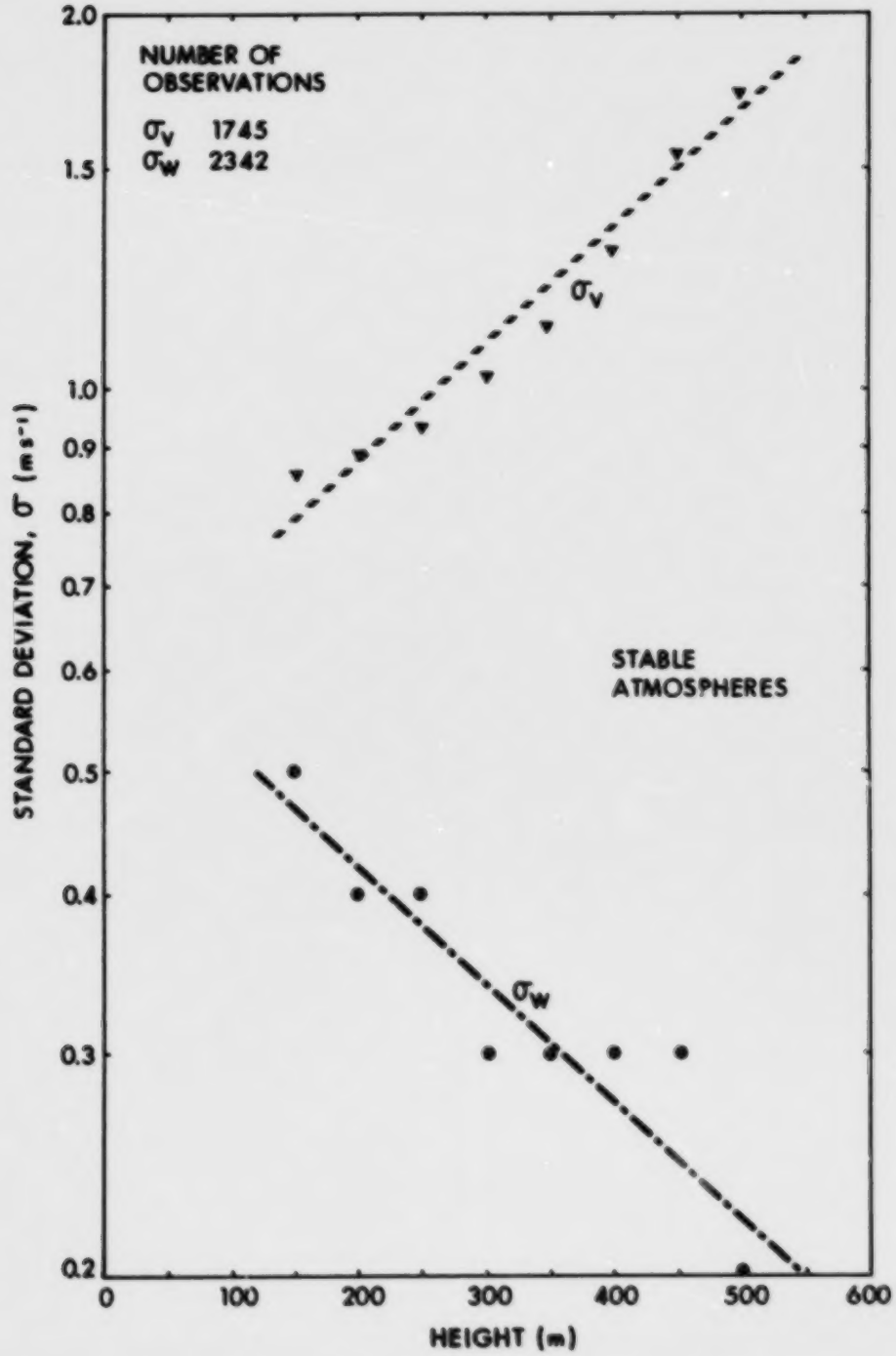

Figure 19. Median values of indicated turbulence components as a function of height.

Components of turbulence intensity (σ_U/U, σ_V/U, and σ_W/U) behaved in a fashion similar to σ_U in so far as they exhibited a maximum at 200 m and varied linearly with height beyond 250 m. These tendencies for the longitudinal component, which were most pronounced for stable conditions, are shown in Figure 20. The maximum at 200 m was expected as speed tends to be at a minimum at this height (Figure 2).

Tendencies of variables to vary linearly when plotted on a semi-log scale such as in Figures 19 and 20 are significant because they suggest that the variables have an exponential dependency. Each of the components of turbulence and turbulence intensity were therefore fitted by least squares techniques to an exponential function of the form $Y = A \exp(BZ)$.

Table 5 presents values of A and B which best fit the observed median profiles. Values of A and B for σ_U and turbulence intensities relate only to heights greater than 250 m. The number of profiles upon which the median is based, as well as the linear correlation coefficients between predicted and observed phenomena, are shown. Correlation coefficients were all greater than 0.90.

Table 5 shows that values of A and B are similar for neutral and stable atmospheric conditions. They are also similar for σ_U and σ_V. The following generalizations are possible for neutral and stable atmospheres:

$$\sigma_U, \sigma_V = 0.50 \exp(0.0020Z) \qquad Z > 250 \text{ m} \qquad (24)$$

$$\sigma_W = 0.65 \exp(-0.0020Z) \qquad (25)$$

and for unstable atmospheres:

$$\sigma_U, \sigma_V = 0.75 \exp(0.0020Z) \qquad Z > 250 \text{ m} \qquad (26)$$

$$\sigma_W = 0.80 \exp(-0.0015Z) \qquad (27)$$

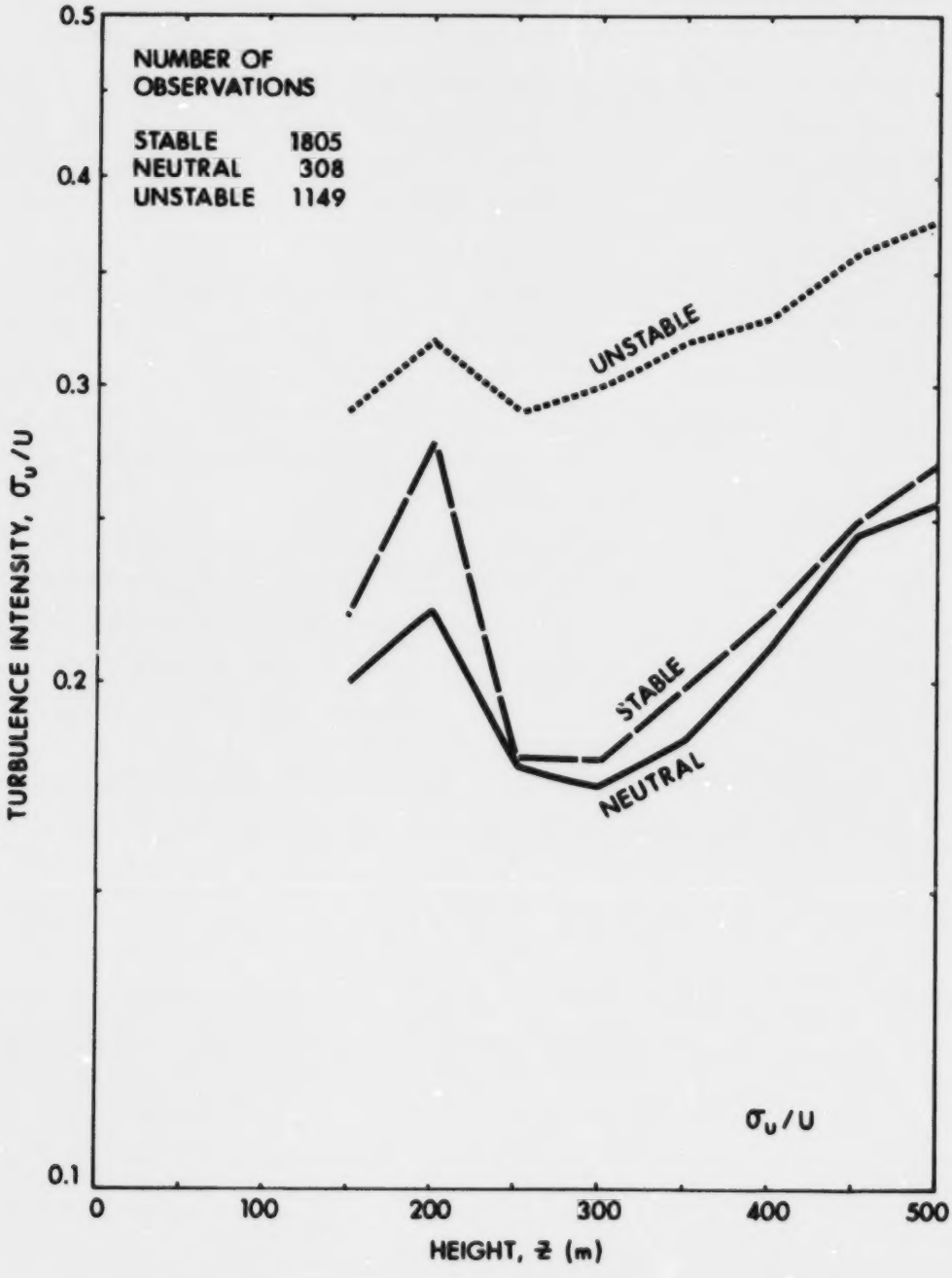

Figure 20. Median values of the longitudinal component of turbulence intensity as a function of height.

Table 5. Least squares regression statistics for profiles of turbulence and turbulence intensities. Parameters were fitted to a relationship of the form Y = A exp (BZ).

Atmospheric Stability	Parameter	A ($m\ s^{-1}$)	B ($m^{-1} \times 10^3$)	Number of Profiles	Correlation Coefficient
Stable	σ_U[a]	0.52	1.9	1820	0.98
	σ_V	0.58	2.1	1745	0.97
	σ_W	0.63	-2.1	2342	-0.92
	σ_U/U[a]	0.11	1.7	1805	0.98
	σ_V/U[a]	0.10	2.3	1745	0.99
	σ_W/U[a]	0.09	-1.7	1521	-0.92
Neutral	σ_U[a]	0.49	2.0	310	0.96
	σ_V	0.50	2.3	306	0.97
	σ_W	0.71	-1.8	328	-0.93
	σ_U/U[a]	0.11	1.6	308	0.94
	σ_V/U[a]	0.10	2.5	306	0.99
	σ_W/U[a]	0.10	-1.7	182	-0.98
Unstable	σ_U[a]	0.77	1.7	1150	1.00
	σ_V	0.75	1.9	1140	0.99
	σ_W	0.82	-1.6	652	-0.94
	σ_U/U[a]	0.22	1.1	1149	0.99
	σ_V/U[a]	0.17	1.9	1140	0.97
	σ_W/U[a]	0.20	-2.2	481	-0.99

[a] Above 250 m

From the above relations the following further conclusions for neutral and stable atmospheres can be derived:

$$\sigma_U\sigma_W,\ \sigma_V\sigma_W = 0.35 \qquad Z > 250\ m \qquad (28)$$

$$\sigma_U/\sigma_V = 1.0 \qquad Z > 250\ m \qquad (29)$$

$$\sigma_W/\sigma_U = 1.3 \exp(-0.004Z) \qquad Z > 250\ m \qquad (30)$$

and for unstable atmospheres:

$$\sigma_U\sigma_W,\ \sigma_V\sigma_W \cong 0.60 \qquad Z > 250\ m \qquad (31)$$

$$\sigma_U/\sigma_V = 1.0 \qquad Z > 250\ m \qquad (32)$$

$$\sigma_W/\sigma_U = 1.1 \exp(-0.0035Z) \qquad Z > 250\ m \qquad (33)$$

It is noted that for σ_U values, (24), (26) and (28) to (33) apply only above 250 m.

Figures 21 and 22 show linear plots with height of the derived expressions for σ_V and σ_W. Relationships suggested by Hanna et al. (Equations (19) and (20)) and Weber et al. (Equations (21) and (22)) are shown for comparison. These were estimated with an assumed value of U_* of 0.4 ms^{-1}. Wind speed for use in the Weber et al equation was estimated by assuming a log law with a value for Z_o of 0.33 m. Figure 21 shows that derived values for σ_V increase rapidly with height in contrast to values estimated from Equations (19) and (21). As illustrated in Figure 22, all predicted and derived values for σ_W decreased with height. The greatest decrease occurred in the values predicted by Weber et al.

Figure 23 shows a comparison between predicted and derived values for the ratio σ_W/σ_V. There are similarities between derived values and those predicted by Weber et al. in so far as they decrease with height. The greatest decrease is shown for the derived values.

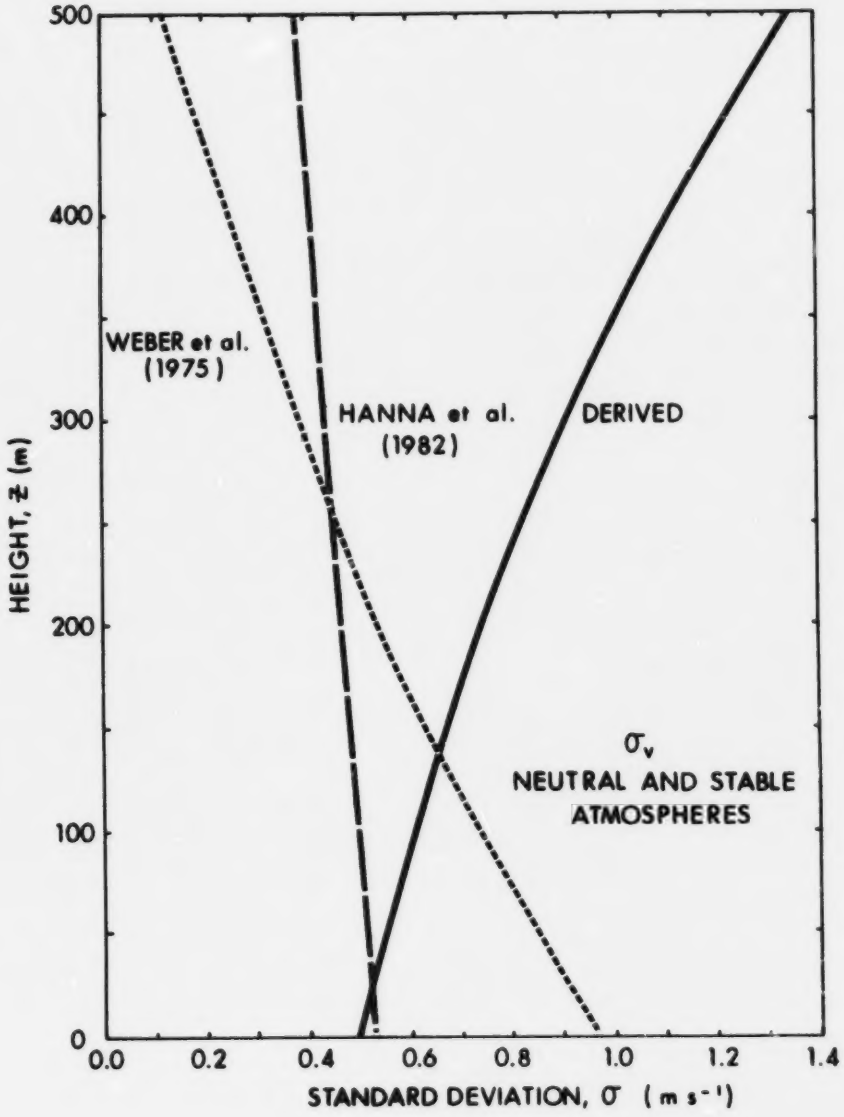

Figure 21: Derived and theoretical values (Hanna et al. 1982, Weber et al. 1975) for σ_v as a function of height.

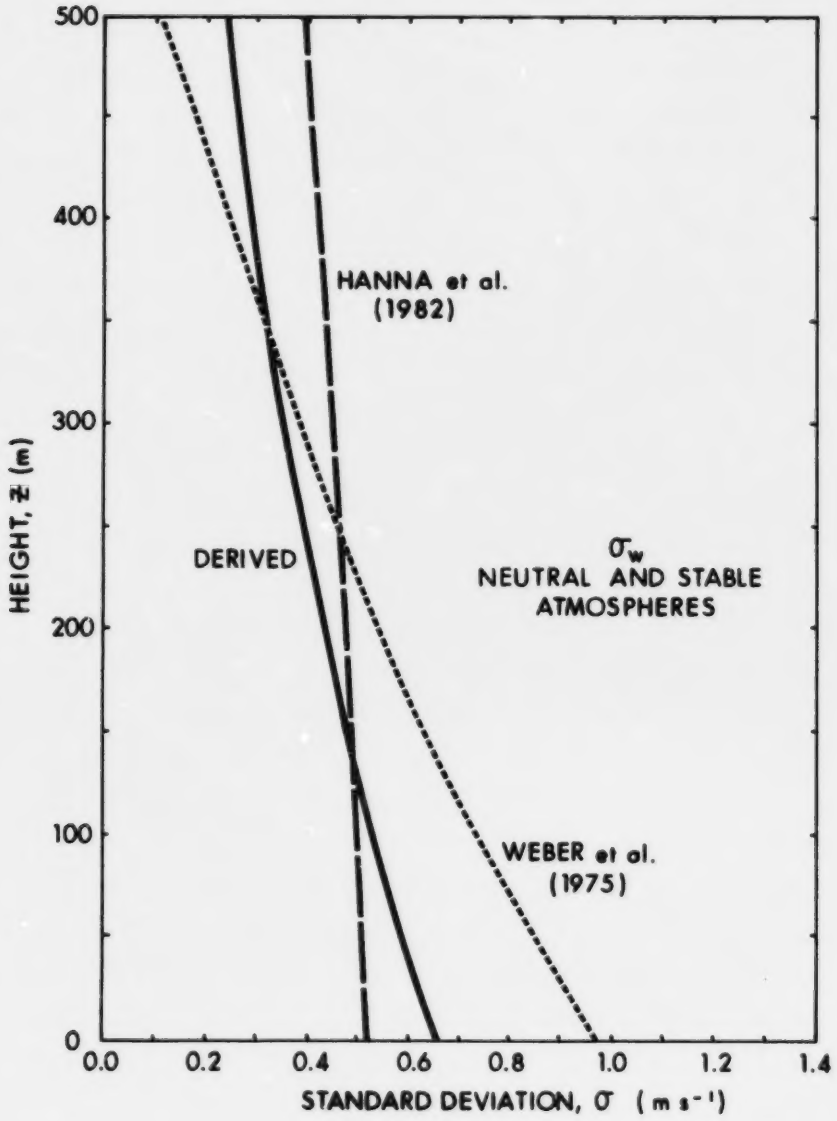

Figure 22. Derived and theoretical values (Hanna et al. 1982, Weber et al. 1975) for σ_w as a function of height.

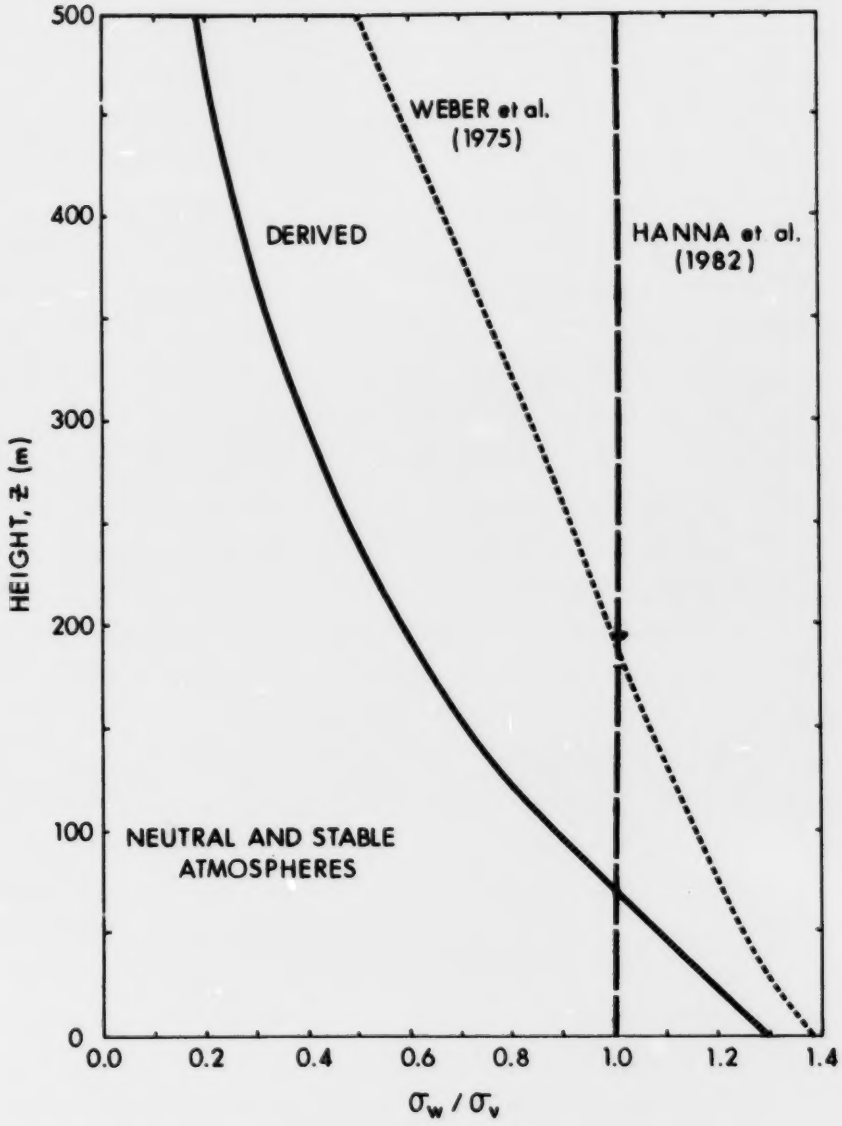

Figure 23. Derived and theoretical values (Hanna et al. 1982, Weber et al. 1975) for the ratio σ_w/σ_v as a function of height.

4. DISCUSSION

Analyses of Doppler wind data have shown a number of interesting features.

4.1 VARIATIONS IN WIND VELOCITY

Both vertical and horizontal winds tended to increase with height. Median vertical winds were slightly positive. Variations in horizontal winds were evaluated in much greater detail than were variations in the vertical wind speeds.

Wind speeds in neutral atmospheres appear to have logarithmic distributions up to a height of at least 500 m. Median values of Z_0 and U_* of about 0.33 m and 0.35 m s^{-1}, derived from a combination of meteorological tower and Doppler radar data, are consistent with expected values for types of terrain such as that which surrounds Ellerslie. Median values of Z_0 and U_*, derived only from Doppler wind data, as collected above 150 m, were much larger than expected. Values of Z_0, which should ideally be a constant, were found to vary over three orders of magnitude. The parameter Z_0 when derived using data above the surface layer thus appears to have little relationship to actual physical roughness elements. This conclusion is supported by the finding that Z_0 was greatest during winter conditions when surface roughness should be least.

Median values and standard deviations of P for the power law function (Equation [13]), as derived from a combination of meteorological tower and Doppler wind information, were found to be 0.28 ± 0.18, 0.17 ± 0.13 and 0.10 ± 0.11 for stable, neutral, and unstable atmospheres, respectively. These are consistent with values found by Touma (1977) from wind observed at lower elevations. Such consistency lends creedence to methods adopted in this report for separating data according to stability. It also tends to confirm the assumption that tower and Doppler radar data can be combined for purposes of examining vertical wind profiles.

These findings cannot be ascribed to unrepresentative data. Evaluations using the power law indicate that the wind information is typical of neutral situations. Clearly, Z_0 does not

appear to be a constant. Dimensional analyses which is used to justify the log law in the surface stress layer does not seem to hold for the atmosphere extending from earth surface to 500 m. This may be because it neglects geostrophic wind effects which are known to be important in the upper atmosphere (Haltiner and Martin (1957)).

Binkowski (1979) has postulated that the friction velocity $U_\star$ will be directly proportional to the horizontal component of turbulence (Equations [5] and [6]). Doppler radar information has shown that the median value of $U_\star$ derived from wind profiles in neutral atmospheric conditions with a proportionality constant of 1/(2.1) is in agreement with theory. The standard deviation of $U_\star$ was, however, much less than the predicted value. It follows that the theory cannot adequately explain the behaviour of $U_\star$. This is because it is necessary for observed and predicted values of $U_\star$ to have both similar means and standard deviations before they can be considered equivalent.

Median values of the diabatic influence function at 150 m were calculated as being about 1.1, 0.7, and 0.4 for stable, neutral, and unstable atmospheres, respectively. These are generally less than the expected values of 6, 1.0, and 0.5. The discrepancy is greatest for stable atmospheric conditions. Ideally, ϕ should be a constant at unity for neutral conditions. In fact, it varied appreciably in the same manner as under other stability situations. The unexpected variations may be related to the fact that the 150 m level is above the surface stress layer for which theory concerning ϕ was derived.

Comparisons of the predicted variation of horizontal wind speeds with height using the log law and power law were made for neutral conditions. Both laws performed about equally well.

Wind directions generally tended to veer with height. Wind backed with height, however, for an appreciable portion of the time (30 percent). Direction changes were greatest near the ground and largest under stable conditions. Magnitudes of the veer, between 10 and 500 m under stable, neutral, and unstable conditions, were about

10, 15, and 30 degrees, respectively. These were consistent with values reported in the literature. From 10 to 20 m, wind direction tended to back, regardless of stability. This behaviour is difficult to explain on the basis of known atmospheric phenomena. It may be that it is due to a misalignment of one of the wind instruments. This possibility should be further investigated.

Comparisons were made between observed variations in wind and behaviour predicted by Wyngaard et al. (1974) on the basis of a higher order closure model. Predicted and observed phenomena were not correlated.

Wind profiles were generally consistent with those observed elsewhere. There was, however, one anomaly. This related to a minimum in wind speed which occurred at about 200 m. There is no explanation for this phenomenon. It could be related to the fact that the top of the mechanical mixing layer and an associated low level jet effect (Blackadar, 1957) should usually be near this height. On the other hand, it may be due to deficiencies in radar operation. Further investigations of these and other possibilities are required before the reasons for this minimum are understood.

4.2 VARIATIONS IN TURBULENCE

Horizontal and vertical turbulence at heights greater than 150 m were essentially independent of wind direction. Horizontal turbulence tended to increase with wind speed. This behaviour is opposite to that observed at near-ground level. Vertical turbulence showed no dependency on wind speed. Frequency distributions of the components of turbulence tended to be log normal.

Longitudinal and transverse components of turbulence were found to be nearly equal. Near ground level the longitudinal component is usually about 30 percent larger than the transverse component. The ratio of crosswind to vertical turbulence (i.e., σ_v/σ_w) decreased with elevation. Horizontal turbulence intensities from 150 to 500 m were of similar magnitude to those observed near the ground. Vertical intensities, however, were only about one half as great. Turbulence under neutral and stable atmospheric conditions was similar. Turbulence fluctuations under unstable situations were about fifty percent greater.

Horizontal turbulence tended to increase with elevation for all stability conditions. A maximum occurred in the longitudinal component at 200 m and coincided with a minimum in wind speed. The vertical component decreased with elevation. It is of interest to observe that horizontal components varied inversely with the vertical component of turbulence. The behaviours are seen, therefore, to be closely linked.

Increases in horizontal turbulence with height were unexpected on the basis of accepted theory which has been mostly derived from near-ground observations. It appears on reflection, however, to be a reasonable phenomenon. It is natural that vertical turbulence will decrease with distance above the ground where it is engendered by mechanical and thermal forces. As vertical mixing decreases, the exchange of momentum between various air layers will also decrease. These air layers are consequently more free to respond to small variations in local pressures which might be induced, for example, by gravity waves. The greater freedom of response results in greater oscillations in wind direction. The same phenomenon is observed near the ground under stable, light wind situations when mechanically and thermally induced vertical turbulence will be small. Under these circumstances horizontal turbulence becomes very large (Leahey and Halitsky 1973; Sagendorf and Dickson 1976).

The tendency for ratios of vertical and horizontal turbulence (i.e., σ_w/σ_v) at elevated levels to be smaller than expected is perhaps the most significant consequence of this study. This is because of its implications concerning diffusion of plumes from strong industrial sources such as power plant stacks. These plumes are often at the 400 m level in the atmosphere. The lower values of σ_w found at this level may mean that plume diffusion to the ground is slower than originally thought. In the meantime, the larger values of σ_v may result in greater horizontal dispersion. The net effect of the smaller σ_w and larger σ_v could thus substantially reduce ground-level pollution impacts from large industrial plumes.

5. CONCLUSIONS

A study has been completed which has resulted in a preliminary synthesis and subsequent analyses of Doppler acoustic radar data collected from September 1, 1982 to August 31, 1983 at Alberta Environment's Ellerslie Air Pollution Meteorology Station. These data were from elevations extending from 50 to 500 m. They therefore provided information from much higher elevations than have been available for most previous wind studies.

Raw data were transposed onto a nine track tape. A subsequent review demonstrated that information from 50- and 100-m levels was of questionable quality. It was, therefore, not used in the data analyses which included an evaluation of height and stability influences upon wind velocity, vector wind components and turbulence.

Wind profile parameters (roughness length, friction velocity, diabatic influence function, power law exponent) were studied with respect to atmospheric stability and frequency of occurrence. Stability categories were defined according to daylight hours. Wind generally tended to behave in a fashion expected on the basis of past information collected at levels below 50 m. The tendency for an appreciable minority of winds to decrease with height and the appearance of an anomalous minimum in the wind speed profile at 200 m was, however, surprising.

Studies were made to determine the behaviour of each component of turbulence at 150 m with wind velocity. Median values did not change appreciably with wind direction. There were appreciable increases in σ_U and σ_V with wind speed. Vertical turbulence, however, was virtually independent of wind speed.

Estimates showed that the roughness length, Z_o, varied over a very wide range of values. It seems clear that this parameter as derived from wind data above the surface stress layer cannot be directly related to physical features on the ground surface. Calculations also indicated that corresponding values of the frictional velocity were unrelated to atmospheric turbulence.

Analyses of turbulence data revealed a tendency for horizontal turbulence to increase exponentially with height. This tendency is accompanied by an exponential decrease in vertical turbulence. Behaviour of this nature, while physically reasonable, was not expected on the basis of present theory. It has implications on the dispersion behaviour of large industrial plumes. There was also a maximum in longitudinal turbulence at 200 m which coincided with the previously mentioned minimum in wind speed. There is presently no explanation for this phenomenon.

Conclusions regarding height dependencies of the various wind parameters were based upon data which extended upwards to 500 m. There were indications that these data may not be fully representative of high wind speed, high turbulence conditions.

Doppler radar data provide information by indirect measurements of air movements. Direct measurements are routinely made by rawinsonde by the Canadian Atmospheric Environment Service at Stony Plain, about 30 km west of the radar site. Data from pilot balloon flights made in the Ellerslie area by Alberta Environment are also available. Information obtained from the above balloon flights could be used to validate Doppler radar measurements.

The stress in this report has been on observational results relating to horizontal winds. Observed behaviour of vertical winds with season and stability has not been considered. More detailed studies of vertical winds would be of interest.

6. RECOMMENDATIONS

This report has presented results from a preliminary analysis of one year of Doppler acoustic radar data. Generalizations have been based upon wind profiles which extended upwards to 500 m. It is recommended:

1. That Doppler derived winds be compared with upper winds obtained at the nearby Canadian Atmospheric Environment Service rawinsonde station at Stony Plain or by Alberta Environment at Ellerslie through use of pilot balloons.
2. That similar analyses be performed on additional information collected during 1983-84 and subsequent years.
3. That a more detailed study be made of the representativeness of data obtained from 500-m profiles.
4. That evaluations be made to determine a physical explanation for the anomalous wind behaviour at 200 m.
5. That studies be made to determine those synoptic conditions under which wind speed decreases with height.
6. That stability classifications be based upon a more quantitative approach than that used in this preliminary analysis.
7. That comprehensive turbulence climatologies be compiled, based upon ranges of wind speed and atmospheric stability categories.
8. That studies be made to determine if the data exhibit diurnal tendencies, especially in wind directions as found by Longley (1968).
9. That the behaviour of vertical winds with respect to season and stability be analyzed.

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8. APPENDIX

Median values of wind speed and turbulence parameters are presented by level, season, and atmospheric stability in Tables 6 to 20. Wind speed parameters include horizontal speed, U; power law exponent, P; longitudinal component, U_o; transverse component, V_o; and vertical speed, W. Turbulence parameters include the longitudinal component, σ_U; the transverse component, σ_V; and the vertical component, σ_W.

Table 6. Median values of horizontal wind speed, U, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	4.6 (2019)	6.7 (1631)	7.0 (570)
Spring	4.3 (2162)	6.1 (2003)	6.3 (1244)
Summer	4.3 (1832)	5.5 (1721)	5.4 (1294)
Autumn	5.5 (2125)	6.9 (1829)	6.7 (856)
Annual	4.6 (8138)	6.3 (7184)	6.2 (3964)

Table 7. Median values of horizontal wind speed, U, (m s^{-1}) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	6.9 (1223)	7.0 (151)	5.6 (176)
	500	6.4 (414)	5.6 (54)	5.4 (61)
Spring	350	6.2 (1011)	8.3 (219)	5.6 (624)
	500	5.9 (545)	6.5 (120)	5.4 (453)
Summer	350	5.5 (823)	8.0 (184)	5.1 (660)
	500	5.1 (590)	4.8 (107)	4.5 (536)
Autumn	350	7.3 (1273)	7.1 (188)	5.2 (321)
	500	7.0 (547)	6.5 (84)	4.2 (181)
Annual	350	6.0 (4330)	7.5 (742)	5.3 (1781)
	500	6.1 (2096)	5.9 (365)	4.7 (1231)

Table 8. Median values of horizontal wind speed power law exponent, P, from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	0.26 (1219)	0.20 (151)	0.21 (176)
	500	0.27 (413)	0.20 (54)	0.22 (61)
Spring	350	0.25 (1009)	0.13 (219)	0.09 (623)
	500	0.24 (543)	0.14 (120)	0.10 (452)
Summer	350	0.31 (818)	0.17 (184)	0.10 (660)
	500	0.32 (585)	0.19 (107)	0.11 (536)
Autumn	350	0.30 (1273)	0.18 (188)	0.11 (321)
	500	0.32 (547)	0.20 (84)	0.10 (181)
Annual	350	0.27 (4319)	0.16 (742)	0.10 (1780)
	500	0.28 (2088)	0.17 (365)	0.10 (1230)

Table 9. Median values of the longitudinal component of wind speed, U_o, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	1.9 (1984)	2.6 (1613)	2.6 (563)
Spring	3.7 (2023)	5.2 (1875)	5.0 (1154)
Summer	3.8 (1789)	4.4 (1696)	3.5 (1280)
Autumn	0.4 (2118)	0.4 (1822)	0.2 (854)
Annual	2.7 (7914)	3.5 (7006)	3.4 (3851)

Table 10. Median values of longitudinal wind speed component, U_0, ($m\ s^{-1}$) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	2.6 (1223)	2.8 (151)	3.1 (176)
	500	2.5 (414)	2.6 (54)	3.2 (61)
Spring	350	4.8 (1010)	7.5 (219)	5.2 (624)
	500	4.4 (545)	5.8 (120)	5.1 (453)
Summer	350	3.6 (823)	6.3 (184)	4.7 (660)
	500	3.1 (590)	4.5 (107)	4.2 (536)
Autumn	350	0.1 (1163)	0.3 (167)	0.5 (299)
	500	0.0 (491)	-0.2 (76)	0.3 (167)
Annual	350	2.9 (4219)	4.7 (721)	4.3 (1759)
	500	2.8 (2040)	3.8 (357)	4.0 (1217)

Table 11. Median values of the transverse component of wind speed, V_θ, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	1.1 (1984)	2.4 (1613)	2.7 (563)
Spring	0.4 (2023)	1.0 (1875)	1.1 (1154)
Summer	0.6 (1789)	1.1 (1696)	1.3 (1280)
Autumn	-0.1 (2118)	-0.2 (1822)	0.3 (854)
Annual	0.5 (7914)	1.1 (7006)	1.2 (3851)

Table 12. Median values of the transverse component of wind speed, V_θ, (m s^{-1}) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	-2.7 (1223)	-2.0 (151)	-1.7 (176)
	500	-2.4 (414)	-1.9 (54)	-1.6 (61)
Spring	350	-1.9 (1010)	-0.7 (219)	-0.4 (624)
	500	-1.8 (545)	-0.4 (120)	-0.3 (453)
Summer	350	-2.0 (823)	-1.0 (184)	-0.4 (660)
	500	-1.8 (590)	-0.8 (107)	-0.4 (536)
Autumn	350	0.0 (1163)	-1.4 (167)	0.5 (299)
	500	-0.4 (491)	-2.1 (76)	1.2 (167)
Annual	350	-1.7 (4219)	-1.0 (721)	-0.5 (1759)
	500	-1.6 (2040)	-0.8 (357)	-0.3 (1217)

Table 13. Median values of the vertical component of wind speed, W, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	0.1 (2033)	0.0 (1822)	0.0 (981)
Spring	0.1 (1839)	0.1 (1706)	0.1 (1292)
Summer	0.3 (878)	0.5 (855)	1.4 (800)
Autumn	0.1 (1840)	0.1 (1680)	0.1 (1145)
Annual	0.1 (6590)	0.1 (6063)	0.1 (4218)

Table 14. Median values of the vertical component of wind speed, W, (m s^{-1}) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	0.0 (1436)	0.1 (181)	0.0 (183)
	500	0.0 (648)	0.1 (94)	0.0 (115)
Spring	350	0.0 (1067)	0.1 (182)	0.1 (442)
	500	0.0 (706)	0.1 (135)	0.1 (379)
Summer	350	0.7 (609)	0.1 (106)	1.0 (138)
	500	0.8 (575)	0.1 (80)	1.1 (123)
Autumn	350	0.0 (1283)	0.1 (164)	0.1 (218)
	500	0.1 (782)	0.1 (99)	0.1 (161)
Annual	350	0.1 (4395)	0.1 (633)	0.1 (981)
	500	0.1 (2711)	0.1 (408)	0.1 (778)

Table 15. Median values of the longitudinal component of turbulence, σ_u, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	0.9 (2003)	1.0 (1516)	1.3 (463)
Spring	1.2 (2157)	1.1 (1947)	1.4 (1069)
Summer	1.3 (1826)	1.5 (1666)	1.9 (1136)
Autumn	1.1 (2095)	1.3 (1701)	1.4 (709)
Annual	1.1 (8081)	1.2 (6830)	1.6 (3377)

Table 16. Median values of the longitudinal component of turbulence, σ_u, (m s^{-1}) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	1.0 (1149)	0.8 (140)	0.8 (170)
	500	0.8 (346)	0.6 (45)	0.7 (50)
Spring	350	0.9 (1049)	1.2 (223)	1.4 (657)
	500	0.9 (497)	1.0 (105)	1.3 (452)
Summer	350	1.5 (802)	1.4 (169)	1.6 (665)
	500	1.4 (526)	1.1 (88)	1.6 (492)
Autumn	350	1.2 (1180)	1.3 (174)	1.3 (305)
	500	1.1 (451)	1.0 (72)	1.1 (156)
Annual	350	1.1 (4180)	1.2 (706)	1.4 (1797)
	500	1.0 (1820)	0.9 (310)	1.4 (1150)

Table 17. Median values of the transverse component of turbulence, σ_v, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	0.8 (1952)	1.1 (1515)	1.7 (460)
Spring	1.0 (2092)	1.3 (1940)	1.7 (1064)
Summer	1.2 (1801)	1.6 (1658)	2.0 (1130)
Autumn	1.0 (2038)	1.4 (1689)	1.7 (700)
Annual	1.0 (7883)	1.4 (6802)	1.8 (3354)

Table 18. Median values of the transverse component of turbulence, σ_v, (m s^{-1}) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	1.2 (1122)	0.9 (136)	1.0 (168)
	500	0.9 (341)	0.9 (44)	0.8 (49)
Spring	350	1.1 (994)	1.4 (220)	1.5 (655)
	500	0.9 (471)	1.0 (105)	1.4 (451)
Summer	350	1.7 (774)	1.5 (168)	1.6 (659)
	500	1.5 (509)	1.2 (86)	1.5 (486)
Autumn	350	1.4 (2123)	1.5 (171)	1.4 (302)
	500	1.2 (424)	1.1 (71)	1.2 (154)
Annual	350	1.3 (4013)	1.4 (695)	1.5 (1784)
	500	1.1 (1745)	1.0 (306)	1.4 (1140)

Table 19. Median values of the vertical component of turbulence, σ_w, (m s^{-1}) at indicated levels by season. The number of observations for each level and season is shown in parentheses.

Season	Level		
	200 m	350 m	500 m
Winter	0.4 (2031)	0.2 (1731)	0.2 (836)
Spring	0.5 (1823)	0.4 (1632)	0.3 (1120)
Summer	0.4 (823)	0.3 (792)	0.2 (715)
Autumn	0.4 (1813)	0.3 (1586)	0.3 (961)
Annual	0.4 (6490)	0.3 (5741)	0.2 (3632)

Table 20. Median values of the vertical component of turbulence, σ_w, (m s^{-1}) at 350 m from profiles reaching indicated levels. The number of profiles for each season and stability class is shown in parentheses.

Season	Maximum Profile Level (m)	Atmospheric Stability		
		Stable	Neutral	Unstable
Winter	350	0.2 (1355)	0.3 (170)	0.2 (179)
	500	0.3 (545)	0.3 (74)	0.3 (97)
Spring	350	0.3 (1015)	0.4 (175)	0.5 (431)
	500	0.3 (601)	0.4 (114)	0.6 (333)
Summer	350	0.3 (578)	0.4 (95)	0.4 (117)
	500	0.3 (534)	0.3 (65)	0.3 (94)
Autumn	350	0.3 (1218)	0.4 (156)	0.4 (199)
	500	0.4 (662)	0.4 (75)	0.4 (128)
Annual	350	0.3 (4166)	0.3 (596)	0.4 (926)
	500	0.3 (2342)	0.4 (328)	0.5 (652)